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INTERSTITIAL ECOLOGY OF THE NIGER DELTA

An actuopaleoecological study

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Abstract. Two cruises (April 1965, May 1966) were made in the Gulf of Guinea for sampling the surface sediment for the purpose of studying the interstitial ecology of the shell-building organisms. On the first voyage nine stations in the western delta and extradeltal Western Nigeria were made and on the second, 45. The samples were taken with a Züllig schlammlot. The following variables were determined on the superincumbent water, the pore-water and the sediment of the top dm of sediment: pH, E_h, dissolved oxygen, salinity, oxidizable organic matter and content of calcium carbonate. The water of the delta has a low degree of transparency due to wave action on the bottom sediment. The top layers of sediment fall largely in the clay fraction. Fecal pellets form a consistent feature of the finer sediments. These derive mainly from molluscs and echinoids. Burrowing organisms are almost everywhere very active and wreak havoc with the primary depositional properties of the sediments. The most common shell-secreting organisms of the epi- and endobenthos are gastropods, pelecypods, scaphopods, foraminifers, ostracods and echinoids. Predaceous gastropods, particularly naticids, constitute an important factor in the population dynamics of the molluscs. They may, however, not play such an important role here as in other parts of the west coast of Africa as, for example, in Ghana. There is some evidence in support of a benthonic phase in the life cycle of *Globigerinoides rubra*. *Quinqueloculina* spp. and *Textilina mexicana* are important, widely distributed, foraminiferal elements. Microfaunistically, the Niger Delta may, with some reservation, be claimed to be characterized by a *Cytherella* sp.–*Textilina mexicana* "association" without this being meant to imply any form of interaction between these species. *Cytherella* sp. is the most widely distributed ostracod, being found throughout the entire delta region, western extradeltal area and in the lagoons. It is often locally numerous.

Leda rostrata, *Labiosa vitrea* and *Crassatella paeteli* are the three most widely distributed pelecypods and may be regarded as forming an association typical for the delta region. Pelecypods and gastropods are roughly equally abundant among the shelled bottom dwellers. They vary between about one tenth and one third in number of the benthonic population. The naticid predators show a statistically significant order of preference of predation. Species of *Ostrea* are the most desired, thereafter *Cardium*. Ostracods are frequently selected as a source of food as are also scaphopods, and many gastropods. Cannibalistic attacks also take place. The widely spread *L. rostrata* and *C. paeteli* are not avidly sought out by the naticids and are seldom drilled.

Transect F, deviates from the others in a number of respects. It shows the highest contents of calcium carbonate, a different pattern for the distribution of trace elements, and a relative rarity of molluscs. This might be related to its positioning at the tip of the delta and the nature of the longshore current-distribution in this region.

Trace element analyses show that many of the elements (Cd, Pb, Zn, V, Cu, Ni, Co, P) tend to increase in concentration with growing distance from the shoreline. Lead and zinc show largely quite high trace concentrations; this is not believed to derive directly from the Pb–Zn-ore bodies of the hinterland. Many of the other trace elements occur in concentrations which lie below average crustal abundance. The elements considered are: Cd, Zn, Pb, V, Cu, Co, Ni, Mn, P, S. Cd is relatively abundant in relation to its concentration in the upper lithosphere. The elements V, Cu, Ni and Co do not show any remarkable properties in distribution apart from the positive relationship with depth. Mn differs in its distributional pattern from that shown by the other metallic elements. Phosphorus shows a pronounced correlation with depth. Some of the sulfur values appear to be rather high; it was found that the samples of transects A, G, H and I with the highest organic contents also show the highest sulfur values. The lowest sulfur values were determined in sand. The content of sulfur in the sediment is relatively strongly correlated with the amount of oxidisable organic substance ($r = 0.76$). The multivariate association between the variables was investigated by the statistical method of principal coordinate analysis.

Sommaire. Deux excursions en bateau (l'une en avril 1965, l'autre en mai 1966) ont été faites sur le Golfe de Guinée pour prendre des échantillons des sédiments dans les eaux de surface. Le but a été d'étudier l'écologie interstitielle des organismes formant des têts. Pendant le premier voyage, neuf stations ont été faites et pendant la seconde 45, dans les régions deltaiques et extra-deltaiques à l'ouest du Nigéria occidental. On a pris les échantillons avec un Züllich schlammlot. Les variables suivantes ont été déterminées sur l'eau de la surface, l'eau des pores et le sédiment du dm supérieur des sédiments: pH, E_h, l'oxygène dissolu, la salinité, la matière organique oxydable et la quantité de carbonate de calcium, L'eau du delta n'est pas bien transparente parce que des lames agissent sur les sédiments de fond. Les couches supérieures des sédiments appartiennent surtout aux fractions d'argile au grain le plus fin. Des particules fécales sont un élément consistent des sédiment plus fins. Elles proviennent surtout de mollusques et d'échinoides. Les organismes qui s'enterrent sont presque partout très actives et se comportent en dévastateurs parmi les dépositions primaires des sédiments. Dans l'épibenthos comme dans l'endobenthos, les organismes à têts les plus fréquents sont des gastéropodes, des pélécypodes, des scaphopodes, des foraminifères, des ostracodes et des échinoides. Les gastéropodes de proie, spécialement les naticides, sont un facteur important pour la dynamique des populations de mollusques. Ils peuvent toutefois jouer un rôle moins important ici que dans d'autres régions de la côte de l'Afrique occidentale, par example au Ghana. On peut avec quelque certitude affirmer une phase benthique dans le cycle de vie de *Globigerinoides rubra. Quinqueloculina* spp. et *Textilina mexicana* sont des éléments foraminifères importants, ayant une grande extension. Pour ce qui est de la microfaune, on peut dire, avec quelque réservation, que le delta du Niger se caractérise par une association de *Cytherella-Textilina mexicana.* Les *Cytherella* sp. ont la plus grande extension parmi les ostracodes de tout le delta, la région extra-deltaïque de l'ouest et des lagunes. A certains endroits, elles sont très nombreuses.

Leda rostrata, Labiosa vitrea et *Crassatella paeteli* sont les trois pélecypodes les plus étendus et peuvent être considérés comme une association typique du delta. Les pélécypods et les gastéropodes sont à peu près également nombreux parmi les formes benthiques à têts. Leur nombre varie entre $^1/_{10}$ et $^1/_3$ de la population.

La coupe F, diffère des autres sous plusieurs rapports. Elle montre la plus grande teneur de carbonate de calcium, une disposition différente des éléments de trace, un nombre de mollusques relativement restreint. Ceci peut être attribué à sa situation au bout du delta et à la répartition des courants longeant la côte.

Les prédateurs naticides montrent, dans leur choix de proies, des préférences qu'il est possible de démontrer statistiquement. Les espèces d'*Ostrea* sont les plus goutées, puis celles de *Cardium.* Les ostracodes sont fréquemment choisi comme aliment, ainsi que les scaphopodes et d'autres gastéropodes. On peut observer aussi des attaques cannibales. *L. rostrata* et *C. paeteli,* tous les deux de large extension, ne sont pas avidement recherchés par les perceurs, et ils sont rarement percés.

L'analyse des éléments de trace montre que beaucoup de ces éléments ont une tendance à augmenter en s'éloignant de la côte. Le plomb et le zinc ont souvent de hautes concentrations; on ne croit pas pourtant que cela provient directement des gisements riches en plomb et en zinc du hinterland. Beaucoup parmi les autres éléments de trace paraissent en des concentrations au dessus de la moyenne parmi les formes à têts. Les éléments déterminés sont: Cd, Zn, Pb, V, Cu, Co, Ni, Mn, P, S.

Le Cd est assez abondant en comparaison avec sa concentration dans la lithosphère supérieure. La répartition des éléments V, Cu, Ni, et Co n'est en rien remarquable, sauf en sa dépendance de la profondeur. Le Mn s'éloigne, dans sa répartition, de celle des autres éléments metalliques. Le phosphore montre une dependance prononcée de la profondeur. Quelques unes parmi les valeurs de soufre notées paraissent assez hautes. On a constaté que les echantillons des coupes A, G, H et I qui contiennent le plus de matières organiques ont aussi les plus hautes valeurs de soufre. Les plus basses valeurs de soufre ont été trouvées dans le sable. La quantité de soufre dans les sédiments a une correlation assez étroite avec celle des substances organiques oxydables ($r=0,76$). Les associations multivariantes entre les variables ont été étudiées par la méthods statistique d'analyse des principaux coordonnés de Gower (1966).

INTRODUCTION

For several years the writer has been concerned with various problems in the paleoecology of the Cenozoic deposits of Nigeria and West Cameroun. Particular interest has attached to the population-dynamical relationships between ostracods and gastropods and between the growth stages of ostracods, salinity, and reconstructions of the morphometric reaction of organisms to environment. Such reconstructions can easily veer to the subjective side owing largely to a lack of documentation for living creatures. It was thought that an investigation of problems relating to the interpretation of the interstitial environment of the delta should prove important in the analysis of the fossil sediments of the urdelta.

A fairly comprehensive account of the paleoecologic results for the Paleogene has been given in Reyment (1966 *a*), where the factors referred to were discussed. It became progressively apparent that studies on fossil material do not have much meaning and are difficult to interpret reliably, unless provided with an adequate basic structure of ecological information. In order to obtain this information analysis of the evolution of the Niger Delta based on elucidating aspects of the interstitial ecology in the Bight of Benin, was initiated.

An orientatory sampling voyage was undertaken in April 1965 on the Nigerian Fisheries research trawler M. V. *Kiara.* This survey was limited to the western section of the delta, where hydrologic conditions differ in many respects from those of the central and eastern parts. The area sampled at that time lay between Lagos and Cape Formoso. The results of this work indicated, that a more expanded study might be expected to yield information of use in interpreting the late Pleistocene to sub-Recent history of the Niger Delta. Consequently, a second more extended voyage was made in May 1966 in connexion with which nine transects, located along the entire Nigerian coastline, were sampled.

The first voyage was made while I was Head of the Department of Geology at the University of Ibadan and was financed by the research funds of the department. The second voyage was supported by a research grant from the Swedish Natural Science Research Council, which organisation also made available funds for the purchase of special equipment and instruments. On both occasions, the unstinting support of the Federal Fisheries Service, Lagos, provided the principal means in the realization of the program. In particular, the aid of the Director, Mr D. Niven, the principal Research Officer Mr E. Bayagbona, Mr V. Sagua and the officers and crew of the *Kiara* is gratefully acknowledged.

In order to have a means of comparing the results obtained with an area outside the Niger Delta, but still geographically near, it was decided to sample an area off the Ivory Coast. The desire to do this could be realized owing to the generous support of the Centre de Recherches Océanographiques, Port Bouet, Abidjan, to whose Director, M. Berrit, thanks are due. Invaluable support was given by the officers and crew of the research trawler M. V. *Reine Poku*. The electrochemical determinations were made on board ship on both projects; analyses were also carried out in the biochemical laboratory of Federal Fisheries Service, Lagos, the chemical laboratory of the Oceanographic Institute in Abidjan and in the microbiological laboratory of the Department of Geology of the University of Stockholm. Dr R. Hallberg, geological microbiologist, University of Stockholm, has contributed much advice on analytical techniques. The laboratory analyses of main constituents have been made by the author, Mr J. de Fries (Lagos), Dr L. Vercesi (Abidjan), and Odont. kand. C. G. Roos af Hjelmsäter (Stockholm). The trace-element analyses were made by Dr Lily Gustafsson (Uppsala) (cf. Appendix) and the X-ray diffraction analyses by Dr A. Jacobsson (Stockholm) and fil. kand. K. Larsson (Uppsala). I am very grateful to Professor Arne Lindroth (Umeå), Dr Ernest Angino (Kansas) and Dr Rolf Hallberg (Stockholm) for reading and criticizing the manuscript. The drawings were made by Mr E. Ståhl, the maps and graphs by Mrs Inga Thomasson and the manuscript typed by Mrs Eva Eklind, all of the Paleontological Institute, University of Uppsala. Financial Support was also given by Nordiska Afrika-institutet.

AIM AND SCOPE OF THE PROJECT

The aim of the project is to determine such interplay as exists between the living organisms of the interstitial sedimentary environment and ecologic factors. The interest in initiating the project was created largely by the nature of the petroleum accumulations in coastal Nigeria and it is hoped that the results will be of use to the Nigerian Petroleum Industry. The scope of research was limited to the interstitial environment of the uppermost 7–8 cm of sediment, because the author believes it is this milieu which is of decisive significance for the accumulation of organic substance. Environmental conditions in the Niger Delta have been largely stable over a long period of time (the period during which the delta has been under formation). An investigation of the existing situation may therefore reasonably be expected to cast light on the interpretation of the paleoecology. Particular attention has been given to the chemical properties of the sediment–water interface. As has been pointed out by Hayes (1964, p. 121), oceanic cores have not usually been collected with the intent to preserve an intact surface. The Züllig sampling apparatus used in the present study was found to be efficient in this respect, although it is hardly robust enough for work in rough weather.

THE NIGER DELTA TRANSECTS

The situations of the transects of the 1966 cruise are shown on the map (Fig. 1). The first transect was run from off Rio del Rey (Cameroun) to near the northwestern coast of Fernando Póo. The second transect was run from the mouth of the Cross River (Calabar River) and the third from the Andoni and Opobo Rivers. The fourth transect was located at the Bonny River, the fifth at the San Bartholomeo River, the sixth off Cape Formoso,

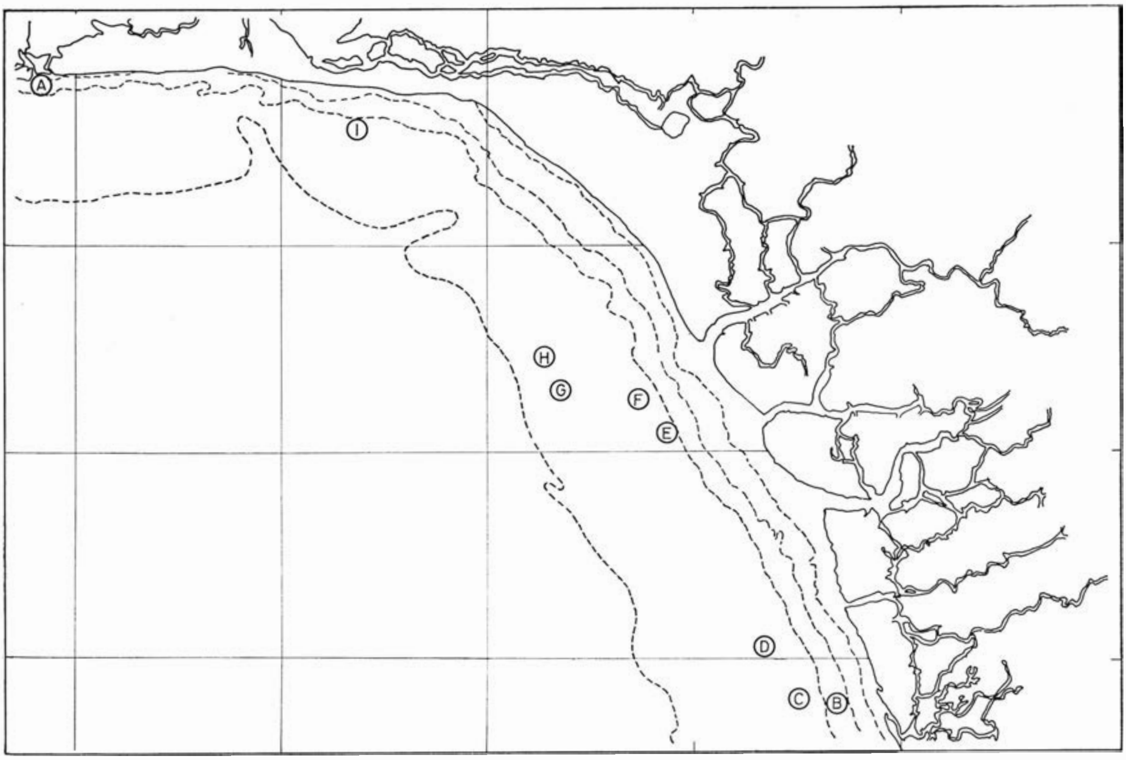

Fig. 2. Stations occupied during the cruise in 1965.

near to the Nun River entrance of the Niger River. The remaining transects were run in the western part of the delta, being located off the Dodo River, at Forcados River, the Benin River, and off the village of Lekki, located on the southern shore of Lekki Lagoon. The stations occupied during the 1965 cruise are shown in Reyment (1966 *b*) and Fig. 2.

THE APPARATUS

The samples of bottom sediment (1966 survey) were obtained with a plexiglas sampling device (*Schlammlot*), manufactured by the firm A. G. Züllig of Rheineck, Switzerland, The 1.5 m long plexiglass tube of 40 mm width is obtainable in two versions, the one consisting of a tube with a 2 dm long hinged doubledoor at one end, which allows the unconsolidated sample to be divided and photographed. The other type is a tube pierced at regular intervals with holes about 1 cm in diameter. These holes are covered with plastic-treated cloth patches to permit sampling by means of a "hypodermic" needle. As the need arises, extra holes may be drilled with an electric hand drill. The tube described allows one to sample small, accurately located points in the sediment and supernatant seawater. The interstitial porewater was isolated with a centrifuge (cf. Manheim, 1966); the samples for analysis were taken immediately after the Schlammlot was brought onboard ship. The samples from the first survey (1965) were taken with an orange-peel grab (Auerbach-Wippermann), which yielded a block of undisturbed sediment with a surface area of 10×10 cm. The electrochemical measurements were made with a Beckman *Expandomatic* pH-meter, equipped with electrodes and auxiliary apparatus for determining the redox potential, and dissolved oxygen. The oxidizable organic content of the sediment was ascertained by means of an approximate chemical method described in Publication 1377 of the British Standards Institute (1961). A volumetric procedure was used for the carbonate analyses. The statistical computations were made on the CD 3600 of the University of Uppsala, using programs developed by the writer. The methods of trace element analysis and determination of phosphorus are discussed in the appendix.

THE MAJOR VARIABLES

1. pH: Two series of pH determinations were carried out on each tube sample. The first measurement was made on the interstitial porewater (referred to as "Site 1" in Fig. 3) of the uppermost layers of sediment (here, and elsewhere in this paper, this expression refers to the uppermost layers of sediment *less* the sediment–water interface zone of oxidized sediment, which in the few cases it was found, is usually about 5 mm thick). The second measurement was made on the seawater immediately overlying the bottom sediment (hereinafter referred to as the supernatant water—the "Site II", of Fig. 3), extracted with the hypodermic. The measured values are shown in Table I. The electrode was calibrated against two buffer solutions of pH 4 and 7 before each determination. Sillén (1963), after a detailed analysis of the problem, concluded that the pH of seawater and the concentrations of major cations are determined by equilibria with the aluminosilicates in the sediments. Oppenheimer and Kornicker (1958, p. 6) consider that low pH (5.4–7.6) in "anaerobic" sediments can be caused by bacterial CO_2 and H_2S; these authors also noted that the pH of such a sediment gradually increases on exposure to air (Oppenheimer & Kornicker, 1958, p. 9).

2. *Redox potential:* This variable was measured on the water of Sites I and II, as for the first variable. To minimize poisoning of the platinum electrode, it was frequently cleaned with fine emery paper of the type used in electron microscopy. The electrode was calibrated against "Zo Bell's solution" before each determination. Control readings were made against a reserve platinum electrode. As a standard procedure, readings were commenced one minute after insertion of the electrodes. The measured values are shown in Table I. For a discussion of some of the problems arising in the measurement of redox potential in marine sediments, reference is made to Hallberg (1968). The values obtained in the present study agree well with those of Hallberg (1968, Table 7) for Dutch tidal flat sediments. The relationship between pH and Eh of the interstitial pore water is shown in Fig. 4. Hallberg (1968, pp. 59, 60) reported a moderately strong negative correlation ($r = -0.46$) between pH and Eh of the sediments studied by him, whereas in the present study, a weak positive correlation ($r = 0.35$) was found.

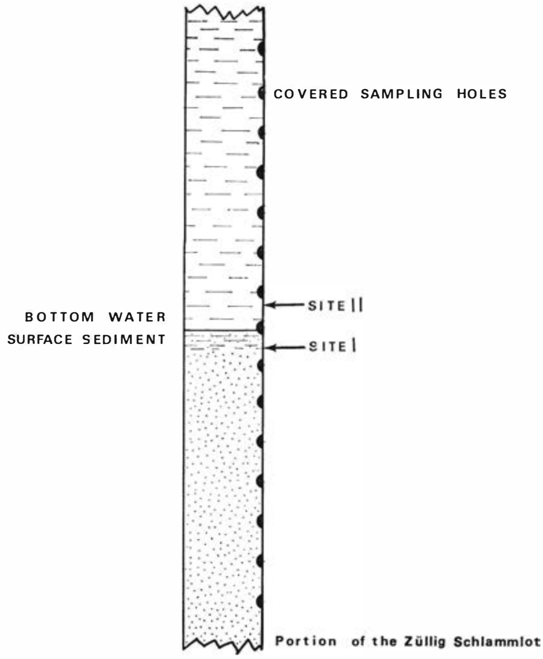

Fig. 3. Schematic diagram of part of a Züllig plexiglass tube showing the two sampling sites.

However, comparison with Hallberg's determinations on the uppermost layer of sediment shows good agreement with our results. This is probably due to our determinations having been made on the uppermost layers of sediment, whereas Hallberg's derive from a greater depth range. The correlation coefficient between pH and Eh of the supernatant water was found to be almost zero ($r = -0.07$). There is also a weak negative correlation ($r = -0.28$) between the pH of the supernatant water and the Eh of the interstitial water. The reverse relationship has a correlation coefficient of zero.

3. *Dissolved oxygen:* Two determinations of dissolved oxygen were made as for the foregoing variables. The Beckman accessory apparatus, Oxygen Adaptor 96260, which employs a gold sensor electrode, was used for these determinations. The sensor was twirled slowly during measuring so as to bring about the requisite flow of water over the membrane. The oxygen is expressed as a percentage of the oxygen contained in air (21 %).

Owing to the small amounts of interstitial liquid available for analysis the writer does not believe that the accuracy attainable by this method can be very great, despite the fact that the determina-

Table I. *Determinations of some of the major variables in the water and sediment (Niger Delta)*

Transect station	Interstitial water pH	Interstitial water Eh (v)	Interstitial water O_2	Supernatant water pH	Supernatant water Eh (v)	Supernatant water O_2	Oxidizable organic matter (%)	$CaCO_3$ content (%)	Depth (m)	Bottom temperature (°C)
A1	7.33	−0.14	3	7.79	+0.19	16	5.5	0.83	7	—
A2	7.74	−0.15	8	7.55	+0.22	12	2.4	3.38	10	—
A3	7.69	+0.08	10	7.77	+0.25	13	3.1	3.83	15	—
A4	7.83	+0.16	8	7.73	+0.24	12	2.1	2.76	30	20.0
A5	7.31	−0.13	9	7.83	+0.28	10	2.0	5.62	65	18.5
B1	7.46	−0.23	8	7.91	+0.21	11	0.8	0.00	6	—
B2	7.30	−0.21	8	7.77	+0.16	13	4.0	1.97	10	—
B3	7.51	−0.21	8	7.96	+0.21	8	5.2	1.61	15	27.5
B4	7.48	−0.17	8	7.86	+0.20	11	5.2	3.33	40	20.0
C2	7.44	−0.20	7	8.30	+0.14	12	2.9	0.68	10	—
C3	7.51	−0.15	7	7.87	+0.18	16	1.2	2.22	15	26.5
C4	7.56	−0.17	8	7.92	+0.22	14	1.0	1.81	30	19.5
C5	7.47	−0.19	8	7.82	+0.24	14	1.7	5.78	75	—
D3	7.60	−0.20	20	7.86	+0.12	20	0.7	14.11	15	—
D4	7.39	+0.12	6	7.69	+0.09	12	1.1	3.83	40	20.0
E2	7.61	−0.09	12	7.95	+0.19	21	2.4	0.38	10	—
E3	7.48	−0.16	7	7.97	+0.15	8	2.1	1.99	15	27.0
E5	7.67	−0.04	5	7.91	+0.16	21	2.6	5.42	60	18.1
F1	7.30	−0.20	20	8.11	+0.12	22	1.7	1.70	6	—
F2	7.37	−0.23	4	7.93	+0.14	14	0.9	1.15	10	—
F3	7.54	−0.15	0.5	8.07	+0.17	19	1.1	12.59	24	29.3
F4	7.52	−0.16	9	7.72	+0.02	18	1.6	16.23	35	19.5
F5	7.43	−0.11	0.5	—	—	—	2.0	7.03	60	17.2
G1	7.67	+0.08	—	—	—	—	0.3	0.83	6	—
G2	7.70	−0.18	6	8.08	+0.10	12	1.7	0.83	10	—
G3	7.44	−0.13	8	7.65	+0.13	16	2.0	1.24	15	24.0
G4	7.51	−0.11	8	7.79	+0.12	16	1.5	7.44	35	21.7
G5	7.59	−0.20	12	7.72	+0.10	13	1.9	1.29	75	—
H3	7.52	−0.10	5	8.07	+0.12	14	2.7	5.10	10	28.5
H4	7.52	−0.17	9	7.89	+0.11	16	1.8	5.22	35	20.1
H5	7.40	−0.20	11	7.77	+0.08	17	2.0	1.38	60	17.8
I1	7.29	−0.21	11	7.95	+0.10	17	0.8	1.02	6	—
I2	7.67	−0.13	9	7.98	+0.10	17	2.1	4.92	10	—
I3	7.55	−0.20	7	7.97	+0.12	20	2.6	5.28	34	26.5
I4	7.63	−0.19	14	7.93	+0.04	18	1.6	2.72	35	20.3
I5	7.56	−0.21	7	7.82	+0.14	14	1.5	3.60	73	18.0
J2	7.56	−0.19	9	7.76	+0.09	17	1.2	2.02	24	—
J3	7.65	−0.17	5	7.64	+0.12	8	2.4	5.28	45	19.6
J4	7.55	−0.19	—	—	—	—	2.6	7.74	75	18.2
Mean	7.52			7.86			2.14			
S.D.	0.13			0.15			1.20			

tions were made within a few minutes of the collection of the sample. None of the samples was found to have oxygen-free interstitial water (cf. Table I), which supports the findings of Hallberg (1968, p. 62). This is of importance for it permits the existence of aerobic microorganisms in sediments which yield negative redox potentials. Hallberg (1968, p. 62) suggested the possibility that aerobic microorganisms inhabit microscopic, oxygenated pockets in the sediment. Certainly, the currently available electrodes for redox determination are far too coarse to enable the identification of such microniches. The procedure used here of centrifuging out the interstitial water produces a mixture of a number of microsystems and is therefore only of averaging importance. The values for supernatant water obtained here agree fairly well with the results of Longhurst (1964, p. 359).

The results of the present work and those of Hallberg (1968) do not support the findings of Kanwisher (1962) who reported oxygen not to penetrate further than 1 cm into a sediment, and Hayes (1964, p. 125) that bottom sediments are

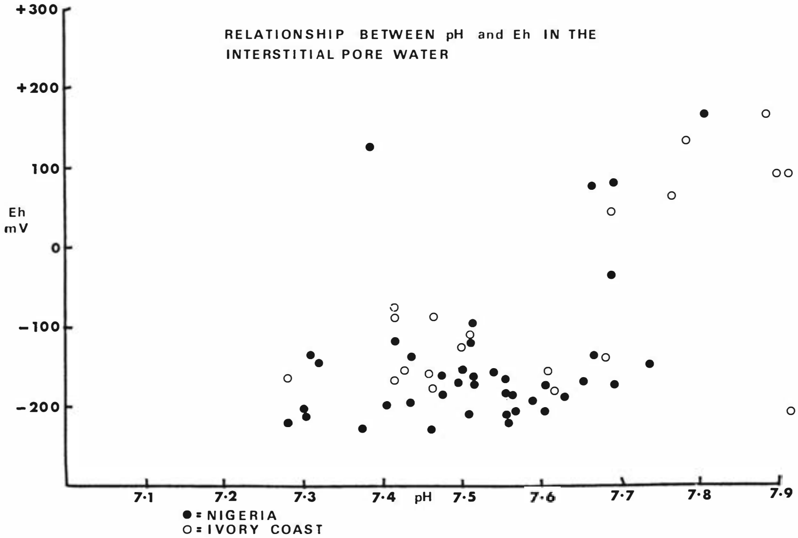

Fig. 4. Relationship between pH and Eh in the interstitial porewater for the samples from the transects in the Niger Delta and the Bandama transect in the Ivory Coast.

anaerobic below a surface layer of 1 cm in thickness.

4. *Salinity:* A so-called "combination electrode" (Beckman Silver Billet 39187, system Ag : AgCl) was tested experimentally for determining the (Cl–) of water from Sites I and II. It was found to be unsatisfactory for determinations in seawater, owing to the interference from other ions. A set of determinations of bottom and surface salinity made during the cruise of 1965 and during the Ivory Coast cruise are summarized in Table II. The Nigerian determinations were made by standard methods of titration and the Ivory Coast analyses by means of a salinometer. For comparison, some information condensed from data of Longhurst (1964) are included. Longhurst's (1964) work deals with the coastal oceanography of Western Nigeria in the northwestern part of the Bight of Benin and thus outside the true regime of the delta. He found stable conditions and maximum temperatures of the water above the thermocline to occur in May (thus at the end of the dry season). The rainy season brings about a lowering of the incident radiation, the temperature and the salinity of the suprathermocline water until minimal values are reached in August–September. In some years the temperature–salinity minimum coincides with the upwelling of cold thermocline water to the surface, which results in a sudden temperature drop and a rise in salinity. The upwelling may be abetted by westerly winds; it is followed by a plankton bloom which introduces species normally confined to subthermoclinal depths.

Table II. *Summary of salinity determinations*

	Sample origin							
	Bottom				Surface			
	N	Mean	S.D.	Range	*N*	Mean	S.D.	Range
Western Niger Delta Cruise of April 1965	5	34.33	4.98	(30.35–35.50) (18 m–73 m)	6	30.14	5.77	25.30–31.64
Lagos transect, May 1962 (Longhurst, 1964)	7	—	—	—		33.30	1.46	31.00–34.56
Bandama transect, Ivory Coast (Cruise of May 1966)	20	35.22	0.74	(33.54–35.68) (20 m–30 m)		— —	—	—

Table III. *Determinations of some of the major variables in the sediment and porewater of the samples from the Bandama transects (Ivory Coast)*

Transect station	pH	E_h (v)	Oxidizable organic matter	$CaCO_3$ content	Depth (m)	Bottom temperature (°C)	Secchi disk visibility (m)
K1	8.05	+0.09	0.22	0.45	10	—	—
K2	7.61	−0.18	2.41	10.00	20	26.71	—
K3	8.11	−0.20	2.78	10.00	30	23.79	—
K4	7.46	−0.18	2.27	14.07	40	22.13	17
K5	7.79	+0.12	1.72	9.53	50	20.93	19
K6	7.42	−0.16	2.06	11.35	60	19.30	20
K7	7.28	−0.16	2.30	11.35	70	18.34	19
L1	7.93	+0.09	0.38	7.26	10	28.19	7
L2	7.69	+0.05	2.66	3.18	20	26.48	7
L3	7.45	−0.16	2.30	12.71	30	24.68	10
L4	7.51	−0.11	1.64	12.26	40	22.00	13
L5	7.41	−0.09	1.64	8.17	50	19.23	15
L6	7.41	−0.08	2.17	9.53	60	19.21	17
L7	7.42	−0.15	2.42	8.63	70	18.17	20
M1	7.88	+0.15	0.43	7.26	10	28.21	4.5
M2	7.68	−0.14	2.32	7.26	20	26.32	7
M3	7.76	+0.07	2.66	19.98	30	23.78	11
M4	7.46	−0.10	1.19	27.24	40	21.38	14
M5	7.50	−0.12	1.55	1.14	50	19.20	15
M6	7.61	−0.15	1.91	12.71	60	18.19	—
M7	7.43	−0.18	2.33	12.26	70	18.02	—
Mean	7.612						
S.D.	0.231						

5. *Oxidizable organic matter:* The chemically oxidizable contents of the upper cm of sediment were determined on dried material. The variable is, for the purposes of the present study, defined as the dried organic substance oxidizable by a chemical oxidizing mixture composed of potassium dichromate and conc. sulfuric acid. Volkmann and Oppenheim (1962, p. 95) concluded that organic matter is more easily decomposed in coarse sediments than in fine owing to the complex organic matter usually associated with the clay minerals and their greater adsorptive capacity coupled with the higher degree of compaction.

6. *Carbonate content:* The carbonate content of the mechanically ground sedimentary samples was determined on 1–2 gm of material (determined as CO_2 and converted to $CaCO_3$). In interpreting the results with respect to this variable, it should be kept in mind, that the carbonate material is derived from not only the shells of living organisms, but also from shelly detritus. Hülsemann (1967), in an investigation of the distribution of carbonate in the surface sediments between Nova Scotia and Hudson Canyon, found that more than 90% of the shelf sediment contained less than 5% $CaCO_3$ [Hülsemann (1967, p. 135)], with a median concentration of 2%. This carbonate material is derived largely from the shells of mollusks, crustaceans and echinoderms, whereas foraminiferal tests are rare. Hülsemann found also that the concentration of $CaCO_3$ does not show a direct relationship to the textural class of the sediment. As noted in the foregoing, foraminiferal remains are in places very abundant in our material, though the samples with the highest contents of carbonate are dominated by the shells of pelecypods.

The $CaCO_3$-content of the material from the Niger Delta varies from zero to more than 16%. The two higest carbonate values occur in transect F. Compared with carbonate values determined on sediments from the Ivory coast (Table III), the Nigerian values are noticeably lower. The relationship between the content of carbonate from all sources and organic matter is shown in Fig. 5.

Comparison with Ivory Coast

Comparable observations made on an area in the Ivory Coast are displayed in Table III. Firstly, the pH is slightly more alkaline than that found for the Niger Delta (pH = 7.61; standard deviation

=0.231); this difference does not reach significance on the 5% level ($t=1.97$). The redox measurements span the same range and show the same relationship to the type of sediment. The content of oxidizable organic material (range: 0.22–2.78%) lies within a narrower range than the delta observations (range: 0.30–5.5%) but the majority of values for both areas fall within the same variational breadth. The content of $CaCO_3$ is higher, thus indicating the greater density of shell-bearing organisms off Bandama. The bottom temperatures show a regular decrease with depth. Another noteworthy characteristic of the Bandama transects concerns the degree of transparency of the water which is appreciably greater than that found in the Niger Delta.

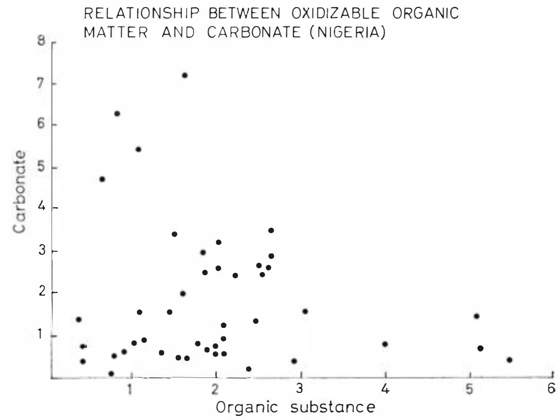

Fig. 5. Relationship between the content of carbonate from all sources and organic matter for the samples from the transects in the Niger Delta.

GENERAL OCEANOLOGIC CONDITIONS

During most of the year there is a stable oceanographic situation in which a layer of warm, homogeneous water overlays a major thermocline which is located at a depth of 30–40 m. Below this depth, there is a layer of colder water which extends to the bottom. The water column over the continental slope consists maximally of five elements which derive from the two water masses. There is, at the top, the supra-thermocline water, which normally shows a temperature range of 26°–29°, and this overlies the upper thermocline water, which has a temperature range of 20°–25°C. These two elements constitute the "Tropical Surface Water". The three underlying elements form the "South Atlantic Central Water" with, uppermost, the interthermocline water (range 15°–25°C), thereunder the lower thermocline water (11°–14°C) and, at the bottom, the sub-thermocline water (< 11°C). Below the 20°C isotherm (lower limit of the upper thermocline) seasonal thermal variation is slight—this is clearly a factor of importance for the benthonic organisms. The location of this thermocline in the Lagos area throughout the

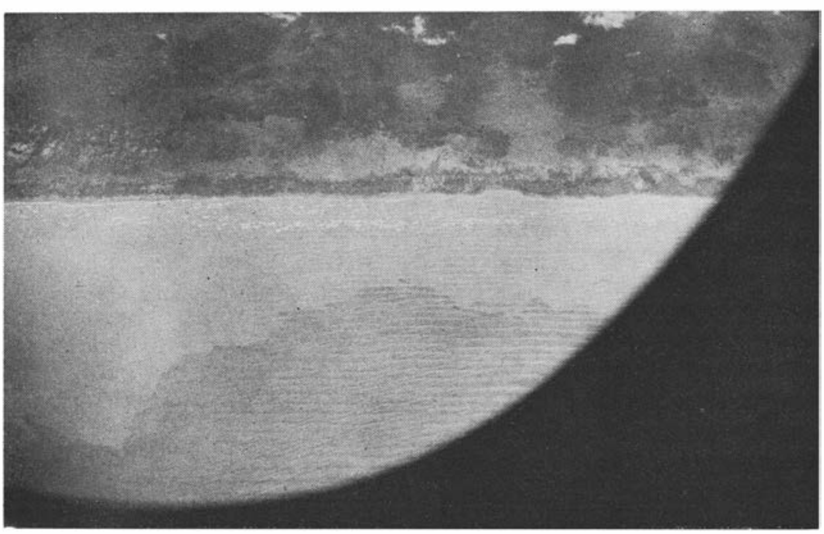

Fig. 6. Wave-activated sediment along the coastline east of Lekki. The irregular boundary with clear water is easily discernible (May, 1965).

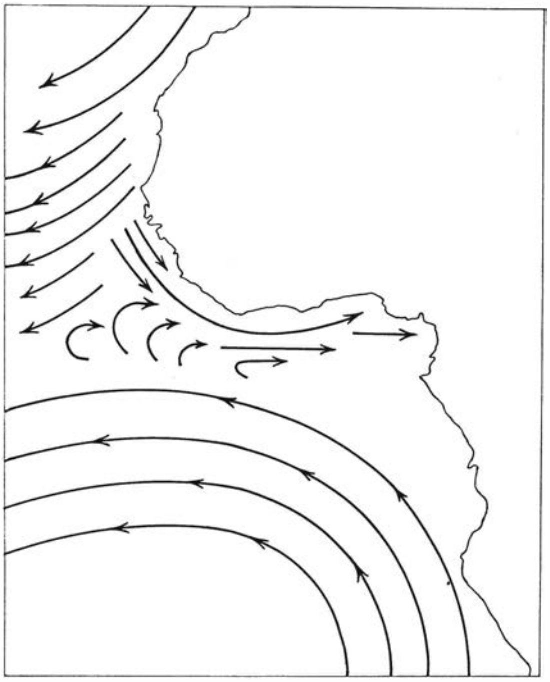

Fig. 7. Sketch showing the main surface currents in the Gulf of Guinea.

year is deepest in September (61 m) and nearest the surface in July (40–50 m). The vertical salinity gradient off Lagos has a maximum value near the lower limit of the upper thermocline (35.7–35.9‰). Below this maximum the values fall off gradually with increasing depth and reach an average value of 34.75‰ at a depth of 400 m. A surface dilution makes itself felt in the Lagos area ("Guinea Water") which extends down to about 60 m. The strongest dilution recorded by Longhurst (1964) was in October 1961 when surface salinities were reduced to 28.9‰; however, the salinity at 20 m averaged 35.03‰. The water transparency of Western Nigeria is low compared with most tropical oceanic standards. Longhurst (1964) records the deepest Secchi disk reading as being 31 m. On April 28th, 1965, in the western flank of the Niger Delta (bottom depth 29 m) at 08.45 hours, the writer made a Secchi disk recording of 12 m and one of 14 m at 10.45 hours on the same day. By way of comparison some Secchi disk recordings made on May 18th 1966 off Bandama, Ivory Coast, ranged from 4.5 m at the nearest inshore stations to 19–20 m at the stations furthest offshore. Longhurst (1964, p. 379) recorded values for the Nigerian coast of 3 through 34 m. Fig. 6 gives a clear picture of the reason for the turbidity of the coastal waters. Intensive wave action is responsible for the continuous upwhisking of the sediment.

The seasons must clearly have a pronounced effect on the nearshore and backshore waters. This is shown, for example, by salinity fluctuations in Lekki Lagoon. The greater part of the delta coast has an average yearly rainful exceeding 300 cm per annum and this marginal zone is backed by a broad region in which the average annual rainfall falls between 200 and 300 cm. The major part of the precipitation occurs during a relatively restricted period and therefore influences the nearshore salinity in particular. This in turn will influence the distributions of the stenohaline organisms.

The entire delta coastline, as well as a broad section of the hinterland, consists of mangrove and freshwater swamp forest and this is backed by a band, 100–250 km in width, of equatorial and tropical rain forest; there is therefore an ample source of supply of vegetable material for the organic component of sedimentation, in addition to the organic substance deriving from marine organisms.

The surface currents

A few words in summary of the prevailing system of surface currents may be in place. The warm Guinea current flows along the continental shelf in a west to east direction. It has its origin in the Canary, North Equatorial and Tropical Counter Currents. Cold water is carried northwards by the Benguela Current but this is largely diverted westwards before reaching the Bight of Biafra. This largely stable current system does, however, go through a period of variability in June–September, when phosphate-rich colder oceanic water tends to invade the Gulf of Guinea. A sketch of the main surface currents of the Gulf of Guinea and surrounding region is given in Fig. 7.

THE NIGER AND BENUE RIVERS

The source of the Niger lies about 750 m above mean sea level but most of this altitude is lost over the first kilometers of its course. Thereafter the average slope of the river is approximately 10–11 cm per kilometer. Within the central delta area the average slope has decreased to 2–3 cm per km.

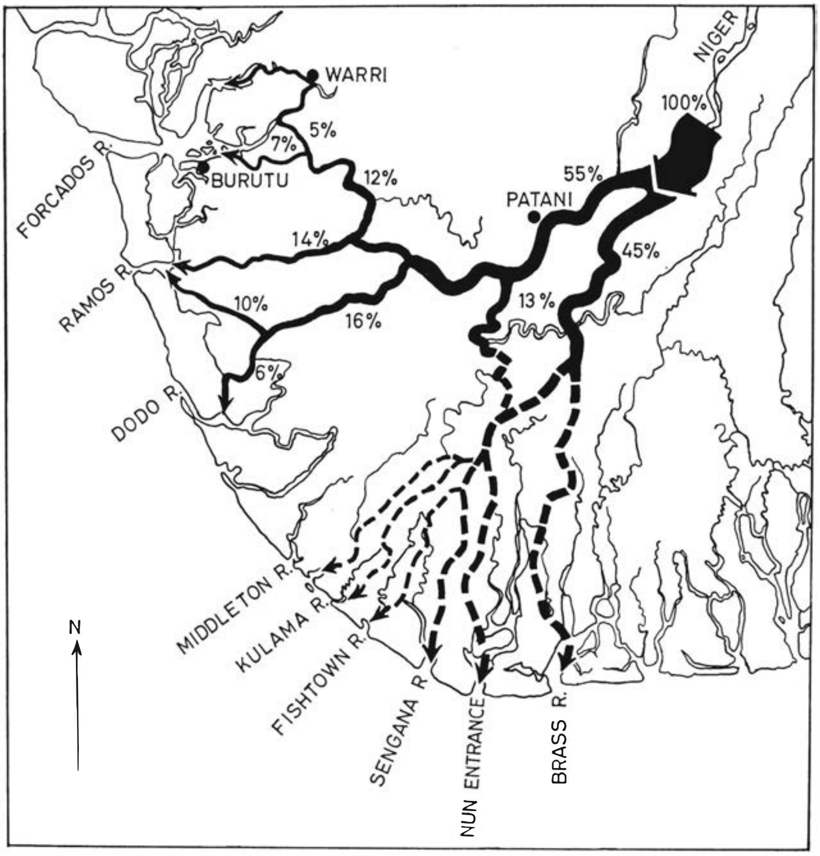

Fig. 8. Sketch map showing the approximate importance of the major streams of the Niger Delta, expressed as a percentage of the total supply of water. (Adapted from Nedeco (1959).)

The Benue River drops 750 m over the first 35 km of its course and at only about 150 km from its source it flows over its own alluvium. The main watershed between the principal rivers is formed by an undulating marshy plain with low hilly ridges and domes of basement rock. The hydrographical center lies on the Jos Plateau from which flow the Delimi, Sungo, Gongola, Kaduna and other rivers. All rivers flowing from the northern Nigerian upland are drained by the Niger–Benue system and the Chad system.

The main difference between the sands of the Niger and those of the Benue lies in the presence of metamorphic minerals in the former and of "volcanic" minerals in the latter (apatite, epidote, brown amphiboles, titanite and augite) (Nedeco, 1959, p. 464). The Niger and Benue do not discharge great amounts of silt. Below the division of the River Niger into the Nun and Forcados Rivers, the river, now flowing through its delta, bifurcates more and more. The decrease in discharge and the decreasing slope, results in the deposition of fine sand, then silt. Fig. 8 shows the approximate importance of the major streams of the Niger Delta.

Allen and Wells (1962) studied dead coral banks in the Niger Delta which lie on top of the Older Sands. Species of *Madracis* and *Dendrophyllia* are predominant. Buchanan (1958, p. 31) reported massive colonies of *Dendrophyllia ramea* (L.) at about the same depth as the Nigerian occurrences. The coral banks, have been used by Allen to determine two subsidences in the delta.

GENERAL NATURE OF THE NIGER DELTA

The history of the Niger Delta may for all practical purposes be considered to have had its begin-

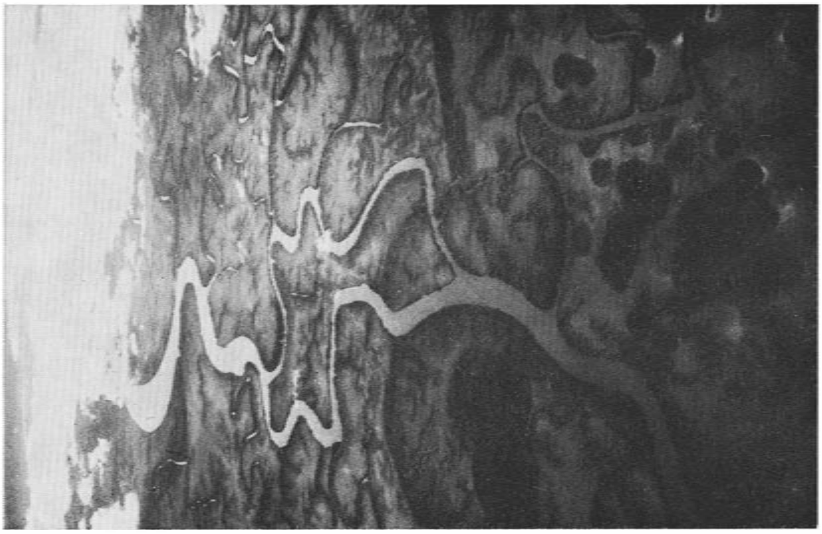

Fig. 9. Meander pattern, Eastern Nigeria (June, 1965).

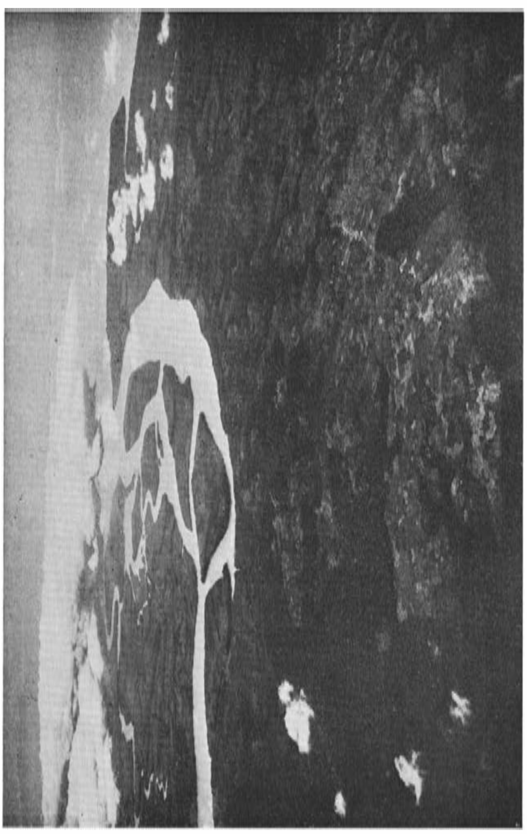

Fig. 10. Mouth of river west of Mt Cameroon (June, 1965).

Fig. 11. Meander with oxbow formation, eastern delta (May, 1965).

ning in late Paleocene time when the delta began advancing in a southerly direction in relation to the regressive phase, which has continued, apart from lesser fluctuations during mainly the Pleistocene, until the present day. The Niger Delta is of classical arcuate form. Within its extent there are several estuarine and lagoonal barrier-island complexes. The delta may be looked upon as mainly sandy, although clays and silts have an important part in its structure. The most recent phase in the growth of the Niger Delta began during the late Wisconsin lowstand of the sea. Submarine canyons formed then; these are now drowned and in some cases no longer in any way connected to a modern watercourse (Fig. 1). As Allen (1965 *a*) pointed out, the oldest stratigraphical unit of the phase of development under discussion is formed by a transgressive strand plain sand. The younger sequence of sediments that follow on from this consists of clays, silts and sands. The barrier islands front a mangrove tidal flat which is succeeded inland by a densely forested river floodplain. The basic features of the Niger Delta have been presented in the Nedeco reports (1954, 1959, 1961). The surface of the mangrove swamp lies between high and low tide and the tidal range is between 1 and 2 meters. Details of the coastline features of the delta are presented in Allen (1965 *a*). Figs. 9–12 show aerial views of creek landscape in the eastern margin of the delta.

Fig. 9 shows a creek meandering into the ocean. Fig. 10 displays the meandering pattern of the lower reaches of a creek in the area to the immediate west of Mt. Cameroun. A meander with oxbow formation is shown in Fig. 11. The distribution of sandbanks in the watercourse segment is typical. Fig. 12 shows a meander pattern in the eastern past of the Niger Delta with billabongs, examples of stream capture and terrace remnants. All pictures were during taken regular flights with Nigeria Airways using a Leica M3 and Kodachrome II color film.

The Niger Delta forms the landward side of the Guinean geosyncline, which is bounded to the east by a fault zone, dotted by volcanic islands, and on the fastland by volcanoes, of which Mt Cameroon is still active (since the arrival of Europeans there have been outbreaks in 1909, 1922, 1955 and 1959, the last being perhaps the most extensive of these). There is now strong evidence available for the crustal unity of South America and West Africa until Lower Turonian time [(Stonely (1966); Reyment (1966 *a*)]. This accords well with the historical development of the delta and the birth of the Guinean geosyncline and consequently the fact that the oldest known sediments in the geosynclinal sequence would appear to be Upper Cretaceous. The general dip of the sediments of the delta is outwards from the rim towards the delta front. The average angle

Fig. 12. Meander pattern, eastern delta, showing billabongs, terrace remnants and stream capture (May 1965).

of dip is greater than that of the present continental slope off the delta and Stonely (1966) has concluded that the overall oceanward dip reflects progressive downwarp of the fringe and offshore areas of the delta.

Fig. 1 gives a reconstruction of the delta front (depths in fathoms), based on echosounding, the Admiralty charts, and data published in Allen (1964). The submarine canyons form the most noticeable features of the submarine topography. These are three in number, the most westerly being the Avon Canyon and adjacent to it there is the Mahin Canyon. The eastern margin of the delta contains the Calabar Canyon. Between these canyons, the edge of the continental slope is marked by gullies and there are gullies further down on the slope. The walls of Avon Canyon consist of clay. Mahin Canyon appears to reach a greater depth than Avon Canyon.

The interstitial ecology of the delta is to a fair extent related to the climatic conditions prevailing in coastal Nigeria. The so-called intertropical front, which marks the boundary between the moist air masses from the south and drier air masses from the north, determines the climate of the area. The monsoonal winds bringing the "wet season" conditions dominate in the coastal region for most of the year but harmattan winds from the north reach the coast occasionally in January and February. The daily temperature range is from about 20°C to 30°C. The average yearly rainfall ranges from 400 mm in the eastern limits of the delta, through 150–170 mm over the central delta, to about 180 mm in the western extreme.

The Atlantic Ocean is a high-energy environment which strongly influences the form of the delta, particularly in relation to the swell of the South Atlantic, with an incoming direction of approximately S 24°W, which, striking the coast obliquely, produces strong longshore currents which run westward, respectively eastward, along the flanks from the midpoint of the delta (Cape Formoso). These currents are sufficiently powerful to divert the sediment carried in by the watercourses, thus hindering the development of the birdfoot type of delta. The spread of sediment is further assisted by tidal currents; their sedimentation in the delta is certainly strongly influenced by reaction of the riverborne material with the seawater carried far inland as a submerged wedge at high tide.

The upper deltaic plain of the continental environment of the delta system comprises mainly sandy sediments with feldspar, iron-hydroxide-oxide-coated sand grains and in the freshwater backswamps and oxbows (Figs. 11, 12) silts and clays, usually rich in plant detritus. This milieu is separated from the truly marine part of the delta by a transitional environment which embraces a brackish zone of mangrove swamps, marsh and flood plains and the lagoons, beaches and barrier bars. Shepard and Dill (1966, p. 272) consider the valleys of the Niger Delta to be more V-shaped than other delta-front troughs but do not rule out the possibility of all having had the same origin. The profiles of the Avon Canyon show terrace or slump-block features which these authors consider comparable to those of the fan valleys in other areas. They also point out that the sides of the Niger Delta canyons do not match.

Hospers (1965) considers, on the grounds of geophysical evidence, that the Niger Delta fills an area once occupied by seawater reaching oceanic depths and that there has been considerable subsidence of the crust. As has already been brought out in the foregoing pages, the present continental slope off the Nigerian coast is a depositional feature, and not a primary one, and this is borne out by the geophysical study reported on by Hospers.

In summary, the history of the cradle of the delta may be reviewed in the following words. There is now reasonable evidence in support of the rift valley origin of the sedimentary basement (Cratchley & Jones, 1965). The greatest accumulation of Cretaceous sediments took place in the Benue and Abakaliki troughs; there is now some evidence for a preliminary phase of rifting during which evaporites seem to have been formed. The Santonian marks a period of tectonic activity with folding and faulting and the intrusion of small igneous bodies and possibly salt-dome injection in the Abakaliki Province. A period of erosion followed, after which a late Cretaceous transgression took place. The next period of uplift was initiated in late Paleocene time. Subsequent to this phase, there has been largely a period of subsidence along the front of the outgrowing delta.

DESCRIPTION OF SEDIMENTS

The sediment arriving in the delta area comes from three sources (Nedeco, 1959). The principle supply comes from the Niger–Benue drainage area. The Niger River passes through Precambrian and Paleozoic metamorphic rocks, Cretaceous and Cenozoic sediments and acid intrusives. The Benue River, which currently is by far the most important single source of sediment, passes mainly through Cretaceous and younger sediments but also Precambrian rocks. The rivers in the eastern margin of the delta flow through basement rock, Cretaceous and younger sediments. Both of these drainage systems are located in areas where lead-zinc mineralization is frequent. A third source of sediment is provided by the rivers in the western margin of the delta. The samples analysed in this paper derive from the fourth major category recognized by Allen (1965 *b,* p. 557), namely, the "continental shelf under delta influence". Usually, the first station of a transect occupied was located near a river mouth bar or on the delta front platform. Subsequent stations were located on the prodelta slope. Allen (1965 *b,* p. 583) has recorded the occurrence of highly turbid water along the coast and at the river entrances. Turbid water is produced by wave and current action in areas well away from river mouths as in the western delta. Fig. 6 shows an aerial view of turbidity in the western delta, off the eastern side of Lekki Lagoon. This is not a permanent state of the coastal water, at least as regards the intensity of the turbidity represented in this picture. Fig. 1 shows the locations of the stations sampled and the compositions of the surface sediments, expressed as histograms. The following account is in terms of the transects shown in Fig. 1, beginning with the eastern extreme of the area.

Transect A was located between Cameroon and the volcanic island of Fernando Póo. The sediments along this entire section were found to be fine-grained and five stations were successfully occupied. The sediment at station A 1 gave a bimodal distribution. It contains numerous algae and fecal pellets, which appear to be the cause of the high organic content. Ostracods and pelecypods also occur. About 27 % of the sediment is finer than 0.037 mm in diameter. The sediment of station A 2 is composed up to about 78 % of particles less than 0.064 mm in diameter; there are algae and occasional ostracods. The sediment at station A 3 is dominated by the finest (silt-clay) fraction, which accounts for more than 70 % of the total weight. Its coarser fractions consist of shells of pelecypods and gastropods, miliolids, fecal pellets, bryozoans, planktonic foraminifers, arenaceous foraminifers, and occasional ostracods. The sediment of station A 4 also falls to 60 % in the silt/clay fraction and again the coarser fractions contain solely shell material, gastropods and pelecypods. Fecal pellets are common. Foraminifers and ostracods occur, including *Buntonia olokundudui* Reyment and Van Valen. The fifth station, located near to Fernando Póo, sampled in the finest sediment of the transect (82 % < 0.037 mm grain-size). This sediment is noticeably rich in shell material and shells and shell fragments constitute the coarser fraction. Scaphopods, echinoids, gastropods, pelecypods and crabs are present and foraminifers are relatively numerous and include planktonic species, among them *Orbulina universa* and *Globorotalia menardil* and the benthonic genera *Uvigerina, Dentalina, Nodosaria* and *Quinqueloculina.* Ostracods are less numerous. The sediment contains fecal pellets.

Transect B was run off the Calabar River. Station B 1 was located inside the mouth of this river, the sediment being mainly fine-grained (71 % < 0.037 mm grain-size). As in the comparable case of station A 1, algae are important. Mica and fecal pellets are present. Arenaceous foraminifers are common and there are rare *Polymorphina.* The sample from station B 2 shows a greater amount of somewhat coarser material including much coarse silt. There is a little mica and there are fecal pellets. Plant material is abundant. The sediment of B 3 is mostly in the slit-clay domain. The high organic content is related to the algal material and plant debris. Both in this, and the previous sample, shell-bearing organisms are scarce. B 4 is slightly coarser and contains shell-building organisms—gastropods, pelecypods, echinoids, planktonic foraminifers, *Quinqueloculina,* arenaceous foraminifers, and rarer ostracods, including *Cytherella* spp. and cytherids. Fecal pellets and wood fragments occur.

Transect C was located off the Opobo River. The first station occupied did not yield a sample owing to the compact nature of the sandy bottom. The sediment of the second station is largely silt and silt-clay and is rich in fecal pellets. The

Fig. 13. Stereoscan photograph of *Globigerinoides rubra* (d'Orbigny). (× 95).

organic material is mostly algae. Shell-bearing organisms are uncommon. The arenaceous foraminifer *Textilina mexicana* (Cushman) (Reyment, 1969) and the ostracod *Cytherella* sp. occur. C 3 was located in finer sediment than the previous station (75 % < 0.037 mm particle diameter) in which fecal pellets are a dominant component. Shell provides the entire source of material in the coarser fractions. Foraminifers of numerous species are present, including planktonic forms, *Quinqueloculina* spp. and *Textilina mexicana.* The most common ostracods are species of *Cytherella* and *Bythocypris.* The sample from station C 4 contains somewhat coarser elements. Fecal pellets are prominent, planktonic foraminifers are numerous, echinoids, arenaceous foraminifers, *Nodosaria,* and *Buntonia olokundudui.* Molluscs are scarce. The sediment obtained at station C 5 resembles in composition that of C 4. Fecal pellets are an important constituent and quartz grains occur scarcely. Planktonic foraminifers, various lagenids and arenaceous foraminifers are present. Occasional cytherids occur.

Transect D, sited off the Bonny River, passed over compact sandy sediment and stations D 1 and D 2 failed to yield samples owing to the hard bottom. The sediment obtained at station D 3 is relatively coarse compared with most other samples. Despite the high content of calcium carbonate, the organic content is low. This indicates most of the shells to belong to dead organisms. This conclusion could be supported by direct observation. Mollusc shells, crabs, bryozoa, worm tubes, and fecal pellets are important constituents. Foraminifers are numerous and include planktonic species, *Quinqueloculina, Planomiliola planispira* de Klasz, le Calvez, Rérat and *Textilina mexicana. Buntonia olokundudui, Cytherella* and various cytherids appear rarely. The sediment obtained at station D 4 is similarly compounded to that of D 3 and the same remarks made for that sample are applicable for it. Many of the mollusc and ostracod shells of D 3 have been subjected to naticid predation. No sample was obtained at station D 5 owing to the compact sandy bottom.

Transect E was located off the San Bartholomeo River. Station E 1 did not yield a sample owing to the compact bottom. The sediment of station E 2 is like that obtained at D 3 and D 4. This sample is interesting as it contains resedimented pieces of partially consolidated material (diameter 0.5 mm–1 mm). Algae and planktonic foraminifers occur. The median for the sediment from E 3 is around 0.05 mm particle diameter. There are shell fragments, planktonic foraminifers, including abundant *Globigerinoides rubra* (Fig. 13), and *Nodosaria.* Station E 4 sampled in sand. Station E 5 was located in sediment composed mainly of particles ranging from coarse silt to clay. The organic components comprise living and dead shell material, including gastropods, pelecypods, echinoids, numerous planktonic foraminifers including *G. rubra, Globorotalia menardii,* and *Orbulina universa, Quinqueloculina* spp., *Nodosaria* and cytherid ostracods. Fecal pellets form an important constituent.

Geochemically, the sediments obtained along Transect F show divergent properties in relation to the material from the other transects. The material from station F 1 is largely in the medium silt–clay range. Mollusc shells are rare, the main organic constituents being algae and the foraminifer *Rhabdammina.* Coarse, sandy fecal pellets are an important element. Sample F 2 is entirely dominated by the fine-silt/clay fraction. Fecal pellets are common, mica occurs and algal material is present. Sample F is, like F 4, much more coarsely textured than F 1, F 2 and F 5. The coarser material derives partly from fine sand and partly from shell fragments. There are gastropods, pelecypods, barnacles, bryozoans crabs, scaphopods. Many of the mollusc shells have been drilled by naticids. Foraminifers are numerous; there are abundant planktonics, including *G. rubra* and

O. universa. Textilina mexicana is a common constituent and there is a punctate form of *Cytherella.* F 4 contains a mixture of fresh and eroded shells in the coarsest fractions and there are waterworn bryozoans and echinoids. The relatively high carbonate value (Table I) is a reflection of the abundant waterworked shell material. There are also planktonic foraminifers, *T. mexicana,* other arenaceous foraminifers, *Cytherella, Bythocypris,* cytherids. In addition to the soft fecal pellets, the sediment also contains hard, patinaed pellets. Porrenga (1967, p. 496) analysed mineralized fecal pellets from the Bight of Biafra by X-ray and found chamosite to be the main constituent down to a depth of 50–60 m and glauconite to be the main constituent at depths ranging from 125 to 250 m. He found the composition of the mineralized pellets to differ from that of the enclosing sediment and the other pellets. The nearshore (depths < 10 m) brown pellets contain mainly goethite and were thought by Porrenga (1967, p. 496) possibly to be oxidized chamositic pellets. Sample F 5 contains *G. menardii, O. universa, G. rubra* as well as other planktonics. Fecal pellets are numerous, ostracods rare. The sediment lacked an oxidized uppermost layer, which may possibly be connected with the virtual complete lack of oxygen in the porewater.

The G-transect was located off the Dodo River. The first two stations were sited in sediment fairly low in organic matter and carbonate, rich in fecal pellets and containing a few arenaceous foraminifers. The median grain size lies in the range of medium silt. Sample G 3 also lies in the medium silt range and contains occasional pelecypods and echinoids, *G. rubra, Cytherella* sp. and *Bythocypris.* There are fecal pellets. Samples G 4 and G 5 are dominated by the fine-silt/clay fraction. Shellbearing organisms are rare, although fecal pellets are important in the sediment.

Stations H 1 and H 2 failed to yield samples due to the compact bottom sediment. The sediment of H 3 is dominated by the fine-silt/clay fraction and contains fecal pellets, fish remain, foraminifers and ostracods, including *B. olokundudui.* The sediment of the fourth station had an unusually thick oxidized top layer; it resembles H 3 in composition. Organisms, apart from arenaceous foraminifers, are rare, although fecal pellets are common. The sediment obtained at station H 5 contains coarser elements. Here organisms are also rare.

Stations I 1 and I 2, off the Benin River, contain fecal pellets but no shell material. There are both hard and soft fecal pellets, mica and a few arenaceous foraminifers. Sample I 3, dominated by the finest fraction, is rich in shell-bearing species and there are pelecypod shells with naticid drill holes. Fecal pellets constitute an important element. There are echinoids, bryozoans, scaphopods, gastropods, pelecypods, crabs, sponges, *G. rubra, O. universa* and other plankton, *Quinqueloculina* spp., *Cytherella, Bythocypris, B. olokundudui, Buntonia* spp. and other cytherids. The sample of station I 4 is similar to I 3, but contains more planktonic foraminifers including *G. menardii* and *Globigerinoides sacculifera.* The main coarser component (< 0.037 mm) of sample I 5 is fecal pellets. Shelled organisms are scarce, there being only a few monoserial and triserial arenaceous foraminifers.

Transect J was sited off Lekki, outside the delta proper. The first station failed to yield a sample owing to the compact, sandy bottom. Station J 2 was located on sediment with a median in the fine sand region. The coarser fractions contain quartz and shell fragments, fragmented *Quinqueloculina* spp., an encrusting species of foraminifers, planktonic foraminifers, drilled pelecypods, gastropods and scaphopods, *T. mexicana,* rare cytherid ostracods and *B. olokundudui.* Samples J 3 and J 4 are deficient in organic material apart from a few foraminifers including *G. menardii.* Fecal pellets are important. This transect crossed over the fossil sediments of the "Older Sands" of Allen (1964).

Remarks

It is interesting to note the considerable difference in the foraminifera found in material from the Abidjan area of the Ivory Coast by Le Calvez (1963) and the forms found in the Niger Delta proper. In many respects, the associations of Western Nigeria tend to resemble the Ivoirian, where *Globorotalia menardii* is the sole planktonic species in the uppermost sample from 40 m. *Orbulina universa* was first found by her in considerably deeper water (200 m) than in our material. Another significant difference lies in the abundance and distribution of *Globigerinoides rubra* (d'Orb.). Glauconite was found in samples from the Lagos transect taken in the cruise of 1965 and in an earlier shorter trip in February 1965.

In agreement with Allen (1964, p. 291) the author believes this to be of fossil origin. Glauconite was otherwise found occasionally in some of the samples from the cruise of 1966. Berthois and Le Calvez (1966) identified glauconite in the Ivoirian samples which may indicate a further agreement of the Ivory Coast with Western Nigeria.

Interest often attaches to the relationship between organic content of a sediment and its clay fraction. Buchanan (1958, p. 12), discussing sediments from the neighborhood of Accra, considered a definite correlation between these two variables to indicate isolation by clay particles of organic material from oxidation and coincident environmental effects. The correlation between the clay fraction and oxidizable organic material of our material is not significant ($r = 0.04$). The correlation with the median is only unimportantly better.

Allen (1965 *b*, p. 557) classified the sediments of the Niger Delta in terms of (1) uniform coarse deposits, (2) uniform fine deposits, (3) layered deposits, and (4) mottled deposits, the latter being secondary in origin. The mottling is caused by bioturbation and fecal pellets. However, the writer has in some samples observed that the youngest sediments may be made up almost entirely of fecal pellets but that these gradually and successively lose their identity down through the sediment. Layering becomes more strongly defined by degrees and this would seem to be of possible chemical origin.

Burrowing organisms play an important part in determining the final appearance going to be assumed by a sediment (cf. Hayes, 1964, p. 122). The present writer's opinion is that virtually none of the finer buried sediments of the Niger Delta can have much if any of their primary bedding preserved owing to the widespread activities of sediment burrowers. The fine-grained sediments of the Niger delta consist mainly of kaolinite and quartz, as shown by X-ray analysis. Kaolinite is formed in intensely weathered soils, typically in the equatorial belt.

THE INTERSTITIAL WATER

The microenvironment represented by the interstitial space of sediments is exceptionally important for many species of ostracods, some species of foraminifers and many species of molluscs, in particular, juveniles (the detailed analysis of the organic constituents of this environment has been limited to forms with shells). The current investigation has indicated, that a large element of the bottom-living ostracod fauna inhabits the interstitial realm. To what extent the living foraminiferal content of the samples actually is confined to the weakly oxidized zone, where such occurs, is difficult to say, as contamination from this layer is hard to avoid in sampling by a suction technique, despite all care. In an investigation made by Reyment and Brännström (1962) on aspects of the physiology of two species of freshwater ostracods a rather surprising result was noted, notably, that both of these forms were able to survive, and even multiply, in a seemingly strongly stagnant environment. The explanation of this apparent anomaly was thought possibly to lie in the definition of the concept of "stagnation". Thus, if a negative redox potential is taken to be synonymous with a complete lack of oxygen (cf. Berner, 1964 *b*, p. 826), then an incorrect representation of the actual conditions is obtained. Hallberg (1968) and Reyment and Hallberg (1967) have indicated, that a negative redox potential does not necessarily imply that there is a complete lack of oxygen in the environment. Brookes *et al.* (1968, p. 400) observed the redox potential measured directly in the sediment to be lower than that measured in interstitial water and thought this might be due to reaction of the electrode with the sediment.

The pH of the sediment was determined to be lower than that of the supernatant water. The redox values measured for almost all of the samples of porewater are mostly negative, with a mean value of roughly -150 mV; this is matched by an approximately equally large positive value for the supernatant water. The dissolved oxygen value for the interstitial water is important, particularly with regard to the distribution of the organisms of the pore space. Brookes *et al.* (1968, p. 401) reported values between 7.7 and 7.8 for the pH of the porewater and Berner (1964 *b*, p. 827) gives an average value of 7.5 for "anaerobic" marine sediments.

CLASSIFICATION OF THE SEDIMENTS

The method of principal coordinates (Gower, 1966) was applied to the information on sedimentary data in Table I to see whether a clustering tendency could be discerned. The plot of the first

Table IV. *Frequencies of major shell-secreting organisms at nine stations (individuals per thousand)*

Station	Pelecypods	Gastropods	Benthonic foraminifers	Planktonic foraminifers	Scaphopods	Pteropods	Ostracods
A	361	269	352	—	5	12	1
B	276	283	200	64	13	25	136
C	130	74	130	487	<1	<1	178
D	35	50	108	690	4	2	111
E	365	339	78	75	<1	<1	142
F	165	232	91	372	14	10	115
G	61	119	247	499	3	16	54
H	31	117	186	571	12	66	17
I	148	296	462	56	17	2	18

eigenvector against the second eigenvector gives four groups. The largest of these groups contains the samples: A 2, A 3, A 4, A 5, B 1, B 2, B 3, C 2, C 3, C 4, C 5, E 2, F 1, F 2, F 5, G 4, G 5, H 3, H 4, H 5, I 3, I 5, J 3, J 4. The second group comprises the samples from stations A 1, B 4, E 3, E 5, the third group those from stations D 3, D 4, E 4, F 4. The fourth group is made up of the samples from F 3, G 1, G 2, G 3, I 1, I 2, J 2. These groupings relate to the overall composition of the sediments, being a multivariate condensation of the information yielded from the fractionation treatment.

There is a fair degree of relationship between the occurence of *Cytherella* sp. and *Textilina mexicana* (Cushman). Twelve samples of 39 contain *Cytherella* sp., *Textilina* or both of these, eight contain both genera, three contain only *Cytherella* and one *Textilina* without *Cytherella.* There is therefore some evidence for a *Cytherella–Textilina* "association". Both genera comprise species which are intimately bound to the substrate. The "association" occurs most frequently in the third classification group, thereafter in the fourth group, followed by the third group (6 of 24) and not at all in the second group. This suggests the possibility of the two species of *Cytherella* and *Textilina* being to a certain extent bound to the granular properties of the sediment.

Each of the sediment fractions was taken as a consistently chosen artificial variable and these were subjected to a principal component analysis. This is clearly a very questionable model as the "variables" represent truncations of a largely continuous system. This is, however, not the full story and, for example, sandy elements will have a different history from the clay fractions. The model here considered has its justification from the viewpoint that it is an expression of the homogeneity of the sediments. If all sediments are identically composed there will be perfect correlation between the artificial variables. Deviations from the hypothesis of an identical grain-size spectrum will show up in the form of lesser correlations and in a decreased weight in the corresponding coefficient in the principal component. The "variables", based on the Wentworth scale, were numbered X_1 through X_8 for the classes 2 mm and finer. The first principal component computed represents roughly equal covariation in X_1, X_2, X_3, X_4, and X_7. The second principal component is dominated by covariation in X_6 and X_7, representing the next finest particles and the third component is dominated by the finest fraction, X_8.

FREQUENCIES OF SHELL-SECRETING ORGANISMS

An inventory of the shell-bearing organisms of the samples collected during the cruise of 1965 was made. Some of the details of this material as well as the locations of the sampling stations were given in Reyment (1966 *b*). Table IV shows the relative frequencies of the main categories of shell-secreting organisms. For convenience of comparison the frequencies are expressed in terms of individuals per thousand. The sediment of station A lies largely within the coarse silt category and glauconite occurs abundantly. In addition to the groups shown in Table IV, bryozoa, balanid plates, otoliths, fish scales and jaws of *Sepia* are found in the sediment. There are naticids, although these are surprisingly few in number considering the high level of predation. An interesting point as

Table V. *Frequencies of major benthonic shell-secreting organisms at nine stations (as individuals per thousand)*

Station	Pelecypods	Gastropods	Scaphopods	Ostracods	Benthonic foraminifers
A	361	269	5	1	352
B	303	311	15	152	219
C	253	144	1	347	253
D	113	161	13	364	348
E	395	366	1	154	84
F	269	375	22	185	147
G	126	245	6	112	509
H	85	322	33	47	512
I	157	314	18	20	490

regards the foraminifers is that the large arenaceous species *Jullienella foetida* (Schlumberger) occurs, although no living individuals were found in this sample. This species has previously been recorded from Ghana (Buchanan, 1958) and the Ivory Coast (Le Calvez, 1963). Another interesting feature is the occurrence of the miliolid genus *Planomiliola*. The Rose Bengal staining technique was used as a guide for picking out individuals living at the moment of capture. It was found in the samples examined that 52% of the naticids were alive at capture while only about 1% of other gastropods. About 2% of the pelecypods were alive, 25% of the benthonic foraminifers and none of the planktonic species. Thirty percent of the species of *Quinqueloculina* and 50% of the *Textilina mexicana*, 10% of the *Cytherella* sp., and 15% of the *Bythocypris* were alive. None of the pteropod material was found to contain soft parts.

Sample C is also almost entirely dominated by the clay fraction. It is interesting as regards the dominant position of the planktonic foraminifers, mostly globigerinids. Ostracods, including numerous *Buntonia olokundudui*, occur. In addition to the groups listed, decapod crustaceans, bryozoans and polychaetes were also found. Station D yielded sediment which was again almost entirely dominated by the finest fractions; it was found to contain polychaetes, crabs, as well as echinoids. Planktonic foraminifers were observed to be the dominant group occurring in this sample; these are largely globigerinid species, including *Globigerinoides rubra*, but about 4% belong to *Globorotalia menardii*. Numerous arenaceous foraminifers occur and in addition to *Textilina mexicana* there are species of *Cyclammina, Hormosina, Lagenammina, Miliammina, Karreriella, Saccammina* and *Sigmoilina*. *Buntonia olokundudui* is the most common ostracod species. *Cytherella* sp. also occurs frequently. The sediment at stations E through H was ascertained to be predominantly composed of clay rich in fecal pellets. Significant features of this sample are the relatively great numbers of *Cytherella* spp., the presence of a multisulcate cytherellid, the relative abundance of *Paijenborchella*, and the large number of *G. rubra*, many of which were living at the time of collecting (cf. Christiansen, 1965). *Cytherella* sp. is the most abundant ostracod and naticids make up about one fourth of the gastropods. There are also remains of decapod crustaceans, echinoids, fish teeth and worm burrows occur. Sample G is dominated by globigerinids with *Quinqueloculina* species also playing an important role. The same arenaceous foraminiferal assemblage as found at station D is present. The sample taken at station H shows a maximum for pteropods and also contains a large number of planktonic foraminifers. It may be meaningful that the occurrences of pteropod shells and planktonic foraminifers are not significantly correlated. The median grain-size for the sediment from station I lies in the coarse silt range. This sample is the second one in which the total number of live individuals was counted the results of which are shown in Table VI. Several dead specimens of *J. foetida* were found as well as some dead specimens of an encrusting foraminiferal species and *Planomiliola*.

Table VI. *Percentage of living to dead shell-building organisms from Station I. (Cruise of April 1965)*

Organisms	Percentage alive at capture
Total pelecypods	37
Natica spp.	21
Other benthonic gastropods	23
Pteropods	0
Scaphopods	0
Total ostracods	36
Planktonic foraminifers	7
Total benthonic foraminifers	26
Quinqueloculina spp.	23
Textilina mexicana (Cushman)	32
Textilina sp.	35

As already noted, the material from both cruises, when collected, contained living individuals of *Globigerinoides rubra* (d'Orbigny) but only occasionally were live individuals of other globigerinids found. Christiansen (1965) has reported on a bottom form of this species. He concluded that *G. rubra* would appear to have a benthonic microspheric multinucleate generation, probably the schizont, and a pelagic, megalospheric, mononucleate generation, probably the gamont. Christiansen made no dogmatic assertions about the absolute validity of his observations. However, the nature of the occurrence of *G. rubra* in the Niger Delta is best interpreted under the assumption of their correctness.

Apart from the probably partly benthonic *Globigerinoides rubra,* the remains of planktonic organisms in the sediments are naturally of allochthonous origin. Although their shells are important as regards their rôle in the chemistry of the porewater of the sediments, the organisms occupy a subordinate position as suppliers of organic substance, partly owing to the readily corruptible nature of the living material of these forms and partly owing to the ample opportunity, provided during their nekroplanktonic phase, for the activity of aerobic bacteria.

Table VII. *Approximate life table for pelecypods of station G (1965)*

Age Interval (unspecified units)	Number of deaths per 1000	Proportion dying in interval	Observed expectation of life
0–1	672	0.672	1.02
1–2	225	0.685	1.08
2–3	551	0.502	1.35
3–4	42	0.808	1.17
4–5	1	0.100	3.00
5–6	1	0.111	2.33
6–7	1	0.125	1.63
7–8	2	0.333	0.83

The greatest part of the planktonic material thus occurs as a sedimentary constituent and consequently cannot be viewed in the same light as the shells of the benthonic organisms. A more realistic representation of the significant shell-secreting components in the sediment is therefore in terms of the benthonic organisms. Table V gives the frequencies of benthonic shell-secreting organisms for the nine stations occupied during the cruise of 1965. These frequencies give a more balanced picture of the relative proportions of the groups existing in the sediment at the moment of sampling. One notes particularly the relatively slight

Table VIII. *Pelecypod species of the interstitial fauna occurring in the Western Nigerian samples*

	Sample occurrence	Geographic range in West Africa
Arca afra Gmelin	AC	Mauretania to Congo (Br.)
A. gambiensis Reeve	AG	Entire west coast
Modiolus stultorum Jousseaume	AC	S. Morocco to Congo (Br.)
Pecten flabellum Gmelin	ABCEFGHI	Mauretania to Angola
P. exoticus Chemnitz	CEG	Mauretania to Angola
Ostrea stentina Payraudeau	AH	Mauretania to Congo (Br.)
Crassatella paeteli v. Maltzan	ABCDEFGHI	Mauretania to Angola
Cardita lacunosa Reeve	ABI	Nigeria to Congo (Br.)
Montacuta bidentata Montagu	A	Entire west coast
Cardium costatum L	F	Mauretania to Angola
C. kobelti v. Maltzan	ABCI	Senegal to Gabon
C. papillosum Poli	AE	Morocco to Angola
Dosinia isocardia Dunker	ABDEFGHI	Mauretania to Angola
Venerupis decussata L	CDEFGH	Mauretania, Nigeria
Petricola pholadiformis Lamarck	EI	Entire west coast
Mactra nitida Spengler	BGI	Mauretania to Angola
Labiosa vitrea Gray	ABCDEFGHI	West coast to Congo (Br.)
Iphigenia rostrata Römer	ABDEGI	Nigeria to Congo (Br.)
Leda bicuspidata Gould	C	Mauretania to Angola
L. tuberculata Smith	CDFG	Ivory Coast to Gabon
L. rostrata Montagu	ABCEFHI	Mauretania to Congo (Kinsh.)
Lima loscombei Sowerby	F	Portuguese Guinea to Nigeria
Arca subglobosa Kobelt	A	Senegal to Congo (Br.)
A. senilis L	ABDFGI	Rio de Oro to Angola

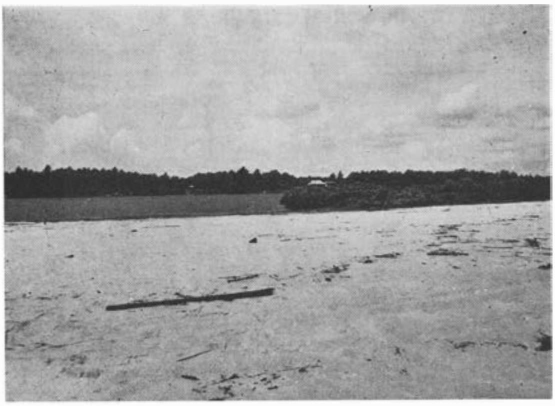

Fig. 14. Lagoon at Lagos (Victoria Beach).

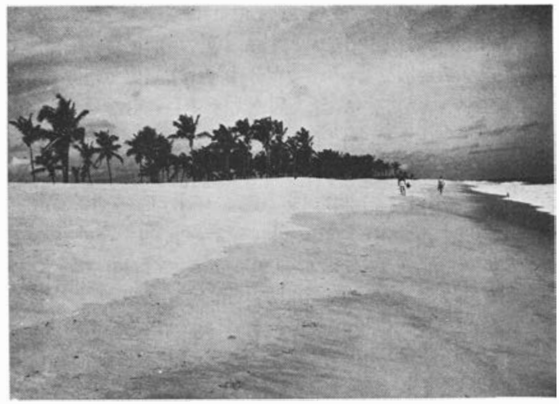

Fig. 15. Victoria Beach, Lagos.

variation in the number of gastropods from sample to sample and the fluctuations in the pelecypod densities are appreciably less. The relative frequencies of the benthonic foraminifers were greatest in the samples from stations G, H and I, in which they were found to make up about one half of the number of total shell-secreting organisms.

Crassatella paeteli was found at all stations, as also *Leda rostrata* and *Labiosa vitrea* and these species may be taken as forming a typical delta pelecypod association.

Remarks

Commonly occurring echinoderms of the Gulf of Guinea are referable to the genera *Amphioplus, Amphiopholis, Rhopalodina* (shallow) *Astropecten,* and *Schizaster.* Echinoids are important bioturbators and bear a large part of the blame for the destruction of primary layering in the sediments.

Numerous genera of polychaetes are found and there are also sipunculoids. Dead shells are sometimes encrusted with the foraminifer *Miniacina miniacea* (Pallas). Species of *Upogebia* may be locally common. Hermit crabs are locally abundant in the lagoons, where they inhabit turrilate gastropod shells. Crabs are locally common; the fragmentary remains of decapods may form an important element of the coarser fractions of some sediments.

Buchanan (1958) found *Dentalium coarti* and *D. maltzani* to be restricted to a narrow zone roughly one km in width, apparently bound in a relationship to the sediment, in his opinion. He also found massive colonies of the coral *Dendrophyllia ramea* (L.) throughout the area (depth > 50 m; bottom calcareous sand, with 68–80% $CaCO_3$). Living corals have not been found in the Niger Delta proper (Allen & Wells, 1962), but seem to occur off Occidental Cameroun according to observations I made in 1953 and 1965. Coral debris is commonly found in Man-o-War Bay near Victoria.

The ostracods seem to show a tendency to occur in differing population densities and to be

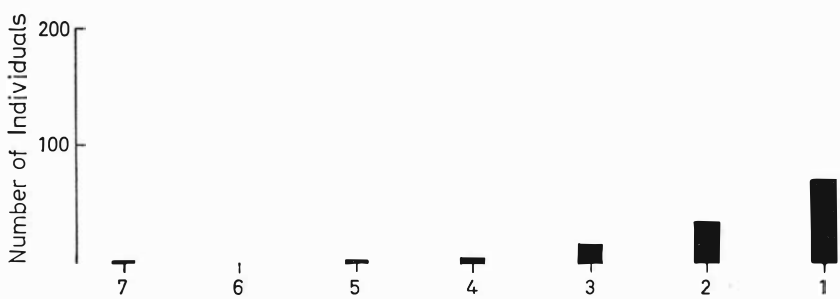

Fig. 16. Size-frequency distribution for pelecypods from station D (1965).

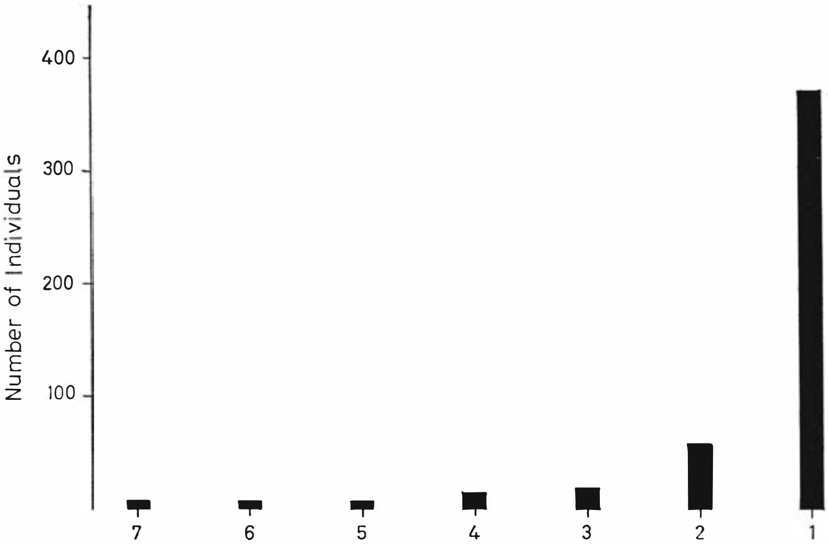

Fig. 17. Size-frequency distribution for pelecypods from station C (1965).

locally abundant. Muus (1967, p. 61) noted that, on the average about 100,000 ostracod individuals per square meter were found by him in Danish fiords (range: 30,000–200,000). These figures are mostly higher than is found in the Nigerian material.

SIZE FREQUENCY DISTRIBUTION OF THE PELECYPODS

The size-frequency distributions for total pelecypods from four stations of the cruise of 1965 are shown in Figs. 16–19. These diagrams, based on the samples from stations B, C, D and H,

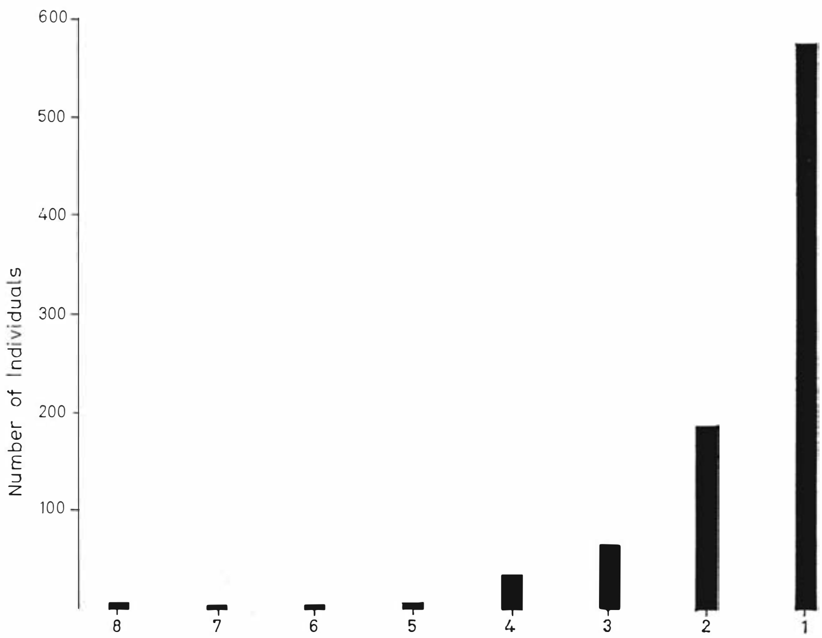

Fig. 18. Size-frequency distribution for pelecypods from station B (1965).

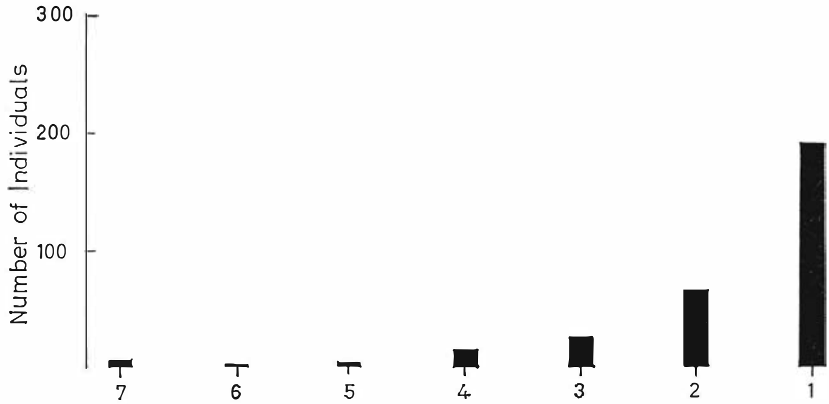

Fig. 19. Size-frequency distribution for pelecypods from station H (1965).

show maximum population density values for the smallest individuals, and a rapid off-tapering towards older growth stages. Although the material refers to all species of pelecypods, with differing growth rates and maximum sizes, the histograms give an approximate, averaging concept of the situation. The overall picture is clearly one of a very high larval and early juvenile mortality. The procedure used by Hallam (1967) was followed in obtaining the size-frequency data. The reason for regarding the pelecypods as a whole, and not analyzing them as separate categories, is that it is not possible, on the grounds of the information presently available on the ontogeny of the pelecypods of West Africa, to identify larval and very young individuals to the species or, at times, even to the genus (cf. Loosanoff, Davis & Chanley, 1966). In general it may mentioned that the results obtained in our study support Hallam's (1967) conclusions in that the size-frequency distributions do not display evidence of transport but rather the results of interaction of normal growth and mortality rates. The figures for sample B will be used to illustrate several points found in the majority of samples. It will be seen that class 8 is remarkable in that it represents an increase in the number of individuals. The life (Table VII) for the population sampled at station B reflects the very high mortality for the early phase of life of the pelecypods. The observed expectation of life at age *x*, the average number of time units yet to be lived by an individual now aged *x*, is very low for the initial periods but becomes successively better and then **falls off.** These figures agree well with what is known about the mortality of young pelecypods. Hallam (1967), in reviewing mortality rates for some species, noted rates of 40–66 %, and even higher under exceptional weather conditions. As concluded in Reyment (1966 *b*), naticid predation cannot be a primary contributing feature to the mortality of the youngest individuals, although it is certainly a major factor for late juvenile pelecypods. It would seem that the mortality of the earliest stages is related to overcrowding.

GASTROPOD PREDATION

The subject of recent naticid predation in the Niger Delta has been considered by the writer on two previous occasions (Reyment, 1966 *a*, 1966 *b*) and it is proposed here to review and supplement these results. As shown in these papers, the drilling predators of the infauna of the Niger Delta belong almost entirely to the *Naticidae*, although shells are occasionally found that have been attacked by muricids. The reason for this disparity is not clear for muricids and naticids are roughly equally represented (*Natica collaria* Lamarck, *N. fulminea* Gmelin, *N. fanel* (Adanson), *N. gruveli* Dautzenberg, *N. turtoni* Smith, *N. adansoni* Blainville and *N. marochiensis* Gmelin for the naticids and *Murex cornutus* L, *M. hoplites* Fischer, *M. turbinatus* Lamarck, *M. angularis* Lamarck, *M. bourgeoisei* Tournouër, *M. varius* Sowerby? and *Thais callifera* Lamarck for the muricids); one would at least expect to find dead shells with muricid holes, in the sediment. Buchanan (1958, p. 25) considered

Table IX. *Gastropod and scaphopod species of the interstitial fauna occurring in the Western Nigerian samples*

	Sample occurrence	Geographic range in West Africa
Gastropoda		
Natica gruveli Dautzenberg		Mauretania to Nigeria
N. fulminea Gmelin		Rio de Oro to Angola
N. fanel (Adanson)		Mauretania to Angola
N. turtoni Smith		Mauretania to Nigeria
N. adansoni Blainville		Morocco to Angola
N. marochiensis Gmelin		Morocco to Angola
N. lacteus (Guilding)	Rare	Senegal, Nigeria
Naticids as *Natica* spp.	ABCDEFGHI	
Clavatula candida Philippi	D	Mauretania to Nigeria
Rissoa spp.	Rare	
Murex cornutus L *M. hoplites* Fischer *M. turbinatus* Lamarck *M. angularis* Lamarck *M. bourgeousei* Tournouër	Occur very rarely	Entire west coast
Eulunella chasteri Dautzenberg	Rare	Guinea, Nigeria
Thais callifera Lamarck	Rare	
Turbanilla senegalensis v. Maltzan	E	Mauretania to Nigeria
Conus papilionaceous Hwass	Rare	Rio de Oro to Angola
Nassa incrassata Ström	Rare	Mauretania to Nigeria
N. obliqua Kiener	Rare	Guinea to Angola
Simnia spelta L	Rare	Senegal, Nigeria
Fusus spp.	Rare (I)	
Crepidula sp.	Rare (E)	
Patella sp.	Rare (CE)	
Scaphopoda		
Dentalium maltzani Dunbar *D. coarti* Dautzenberg as *Dentalium* spp.	ABCDFGHI	Senegal to Congo (Kinsh.) Guinea to Gabon

Natica fanel to be the most frequent cause of mortality in the 15–35 m zone off Accra. He found 273 out of 436 dead shells to have been drilled by naticids. This is an extremely high predation figure and exceeds anything I have found in the Niger Delta.

There is a definite order of preference shown by the naticids. *Ostrea* is clearly selected preferentially; *Cardium papillosum* Poli is also highly favored as well as other sculptured pelecypods, while a number of smooth-shelled pelecypods, despite their great abundance, are among the least-desired sources of food. Naticids drill juvenile and adult individuals of species of the ostracod genera *Cytherella* and *Bythocypris*. The size of the hole drilled is not correlated with the size of the prey animal, hence large drills are not discouraged by the small size of the prey and will attack juvenile pelecypods and ostracods (Reyment, 1966 *b*).

A point of some interest, and one which requires a special investigation, is that naticids appear to be active drillers at such a shallow depth as 4 m, both in the Niger Delta, the extradeltal area of Western Nigeria and in Ghana. The best known naticid, *Lunatia nitida* Donovan, however, lives at 30 m in the North Sea.

The naticids also occasionally attack the strongly ornamented ostracod *Costa*, also *Leguminocythereis, Bradleya, Hemicythere* and even such a minute form as *Cytheropteron*. In some cases the hole drilled is more than two thirds of the length of the carapace.

It has not been found possible to determine any clearcut regularity in the intensity of attack by the drills. However, a group embracing the pelecypod species *Pecten flabellum, Crassatella paeteli, Leda rostrata, Venerupis decussata, Mactra nitida* and *Arca subglobosa* are seemingly experienced as equally desirable by the naticids (Reyment, 1966 *b*).

Table X. *Overall totals for pelecypods in the Western Nigerian samples*

	Samples									
Species	A	B	C	D	E	F	G	H	I	Total
Pecten flabellum	5	11	12		3	1	1	3	10	46
P. exoticus			3		1		1			5
Arca afra	2		9							11
A. gambiensis	2						1			3
A. subglobosa	1									1
A. senilis	1	6		3		1	4		6	21
Modiolus stultorum	1		9							10
Ostrea stentina	2							5		7
Crassatella paeteli	8	27	54	6	8	18	5	7	12	145
Cardita lacunosa	8	8							38	54
Montacuta bidentata	3									3
Cardium costatum						1				1
C. kobelti	1	1	6						3	11
C. papillosum	7				2					9
Dosinia isocardia	2	5		1	1	3	1		8	21
Venerupis decussata			33	1	1	6	3	2		46
Petricola pholadiformis					1				3	4
Mactra nitida		11					1			12
Labiosa vitrea	7	3	48	4	2	1	1	2	6	74
Iphigenia rostrata	2	2		1	1		1		3	10
Leda rostrata	2	1	30	7	2	4	1	1	10	58
Lima loscombei						1				1
Leda tuberculata			54	1		5	1			61
L. bicuspidata			12							12
Total pelecypods	54	75	270	24	22	41	21	20	99	

Naticids are endobionts and live in the uppermost layers of sediment where they, incidentally, cause havoc with primary sedimentational structures. Muricids are entirely epibenthonic forms and will eat carrion which is a thing naticids never do. Species of *Nassa* occur fairly commonly in the delta; these are also eaters of carrion. A list of species identified in the material from the western part of the Niger Delta and the extradeltal part of Western Nigeria is given in Table VIII. These identifications are in many cases based on juvenile individuals. *Arca afra* is best known as a rock dweller; in the Niger Delta it is a minor faunal element. *Crassatella paeteli* is a very characteristic form of many of the sites sampled. The specific determinations of the naticids are grounded on adult and near-adult individuals; however, most of the naticids found in the sediments are juveniles and as such not possible to break down into species. This is also true for most other gastropods occurring. *Nassa obliqua* Kiener and *Tricolia pullus* L are two commonly drilled gastropods.

As shown by Tables VIII and X, the most widely spread and most numerously occurring pelecypod is *Crassatella paeteli,* but this is one of the least desirable items of food for the naticids (predation proportion 1 : 17.7). *Leda rostrata* also occurs at all places sampled in the delta but is a further species arousing little interest in the naticids (predation proportion 1 : 19.3). Buchanan (1958) reports the drilling barnacle *Kochlorine* to be active in Ghanaian waters. It was identified in our material. The relative abundance figures given in Table X express the number of pelecypod shells occurring in 100 gm of sediment. The greatest density of individuals is found in sample C, which possibly represents a local enrichment of shells of schill type.

Reyment (1966 *b*) found that there is a slight but statistically significant preference shown by *Lunatia nitida* for the left valves of pelecypods of the North Sea (confidence interval 0.435–0.471). The confidence interval for the Nigerian pelecypods was determined to be 0.396–0.532 and there is therefore no apparent preferred orientation of the shell represented in this material. Kornicker *et al.* (1963) did not find Texan naticid drills to show a preference for either valve of a pelecypod species.

In summary, naticids occur throughout the

Table XI. *Results of analyses for Cd, Pb, Zn, V, Cu, Ni, Co, Mn, P, S for 5 transects; (values in ppm)*

Transect Stations	Cd	Pb	Zn	V	Cu	Ni	Mn	P	S	Co
A1	2	42	107	110	26	46	1120[a]	660	5700[a]	26
A2	2	44	133	103	43	46	530	740	3500	22
A3	2	46	203	107	25	62	470	720	4100	26
A4	3	47	180	124	37	60	510	830	2000	29
A5	3	44	134	120	30	70[a]	520	930	3100	31
F1	2	38	121	80	21	35	360	500	1590	20
F2	2	34	96	107	31	47	520	610	3200	30
F3	1	14	37	49	19	15	370	460	600	10
F4	2	35	70	75	18	33	400	650	960	22
F5	2	34	101	72	85[a]	37	290	580	360	18
G1	1	26	63	52	39	6	470	260	90	7
G2	1	28	39	55	13	15	370	280	340	11
G3	2	39	98	99	44	43	360	570	2200	19
G4	3	40	218	108	42	52	400	780	760	23
G5	11[a]	45	181	100	63	62	570	870	1320	26
H1	1	26	54	36	18	7	280	200	90	5
H2	1	29	58	43	38	12	330	250	190	7
H3	2	38	87	99	30	43	430	480	2370	2
H4	2	40	125	124	48	54	440	790	970	20
H5	2	40	137	111	45	54	660	940	700	23
I1	1	30	97	61	24	20	365	350	730	11
I2	1	32	150	75	24	23	455	510	1800	14
I3	2	39	98	104	26	51	620	630	4200	32[a]
I4	2	49[a]	360[a]	103	40	61	380	800	1390	30
I5	3	46	139	127[a]	57	55	750	980[a]	910	31
Mean	2.24	37.4	121.4	89.8	35.44	40.36	478.80	614.80	1657	19.80
S.D.	1.95	7.30	71.27	27.62	16.29	19.12	175.80	228.69	1572	9.11
Approximate content in seawater	0.0001	<0.005	<0.01	0.002	<0.004	<0.002	<0.002	<0.1	884	0.0005
Crustal average	0.2	12.5	70	135	55	75	950	1050	260	25

[a] Maximum value for each element.

whole area of the Niger Delta and are locally abundant. In addition to numerous pelecypod and gastropod species the naticids attack other naticids and also muricids, scaphopods, which are particularly sought after, ostracods and, in rare cases, even foraminifers.

There is variation in the shape of the naticid boring from sample to sample, due possibly in part to variation in shell thickness. The ranges of variation found in some samples for the outer and inner dimensions of the boring may perhaps be correlated with shifts in the composition of the predator fauna. The naticids show a statistically significant preference for boring the central area of pelecypod shells and also many ostracod carapaces.

DISTRIBUTION OF TRACE ELEMENTS

Transects A, F, G, H and I were chosen for trace-element analysis, as material is available from all five stations. The samples were analysed for the metals Cd, Pb, Zn, V, Cu, Ni, Co and Mn and also P and total sulfur. The analyses were performed by Dr L. Gustafsson, Department of Analytical Chemistry, University of Uppsala by atomic absorption spectrophotometry and other procedures (see Appendix). The results for all trace element analyses and those for S and P are shown in Table XI and, excluding Cd, in Figs. 20 through 28.

Cadmium. The cadmium contents are the lowest of all the elements considered but represent, nevertheless, a great enrichment in relation to seawater. Using the "concentration factor" of Mullin and Riley (1956), defined as the concentration of a trace element in an air-dried sample divided by the mean concentration of the trace element in seawater (for Cd, 0.133 μ/l), one obtains an average concentration factor ($\times 10^{-3}$) of 19.82. The plot of the Cd values against depth do not indicate any

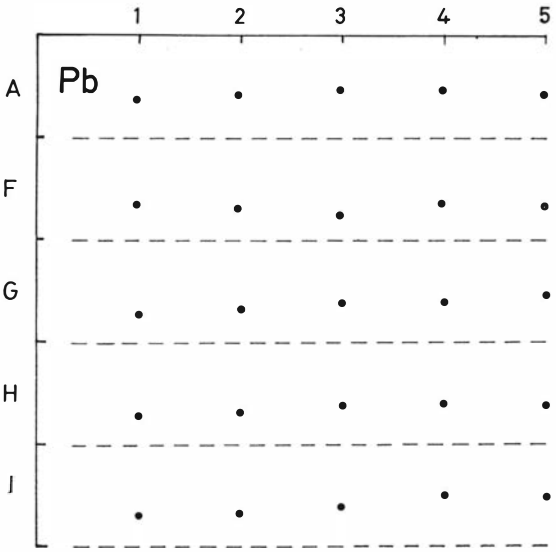

Fig. 20. Variation of content of Pb in sediment with depth for each of the complete transects. The figures 1 through 5 denote the stations.

particular trend. However, the correlation coefficient between these variables is 0.48 (significant on the 2%-level) which suggests that the content of cadmium has a tendency to increase with depth. Station G 5 shows the exceptionally high value of 11 $\mu g/g$. This relatively high concentration could possibly derive from the soft parts of certain molluscs, although the station in question yielded a sediment poor in organisms and an oxidizable organic content of 1.9. All of the values are well in excess of the cadmium content of the upper lithosphere (0.5 $\mu g/g$). Values as high as 38 and 16 $\mu g/g$ (soft parts of gastropods) have been reported by Mullin and Riley (1956). These authors remarked on the low cadmium content of calcareous shells. On the whole, however, low as most of the values obtained in this analysis may seem, they are nevertheless mostly greater than those obtained by Mullin and Riley.

Lead. Transects G, H and I indicate a definite tendency for the content of lead in the sediment to increase with depth (Fig. 20). The correlation coefficient between these variables is 0.55, which is significant on the 1%-level. Reference to Table XI shows that lead is very highly concentrated in the sediments in relation to its contents in seawater and that transect A (range: 42–46 $\mu g/g$) shows a consistently high set of values, although stations G 4 and G 5 gave values of 40 respectively 45 $\mu g/g$ and stations I 4 and I 5 gave 49 respectively 46 $\mu g/g$. Angino (1966), dealing with quite a different type of environment (no river drainage, weathering largely absent, for example), reported values for lead of always less than 50 ppm and zinc less than 200 ppm (Angino, 1966, p. 944). These figures may be applied, with only slight modification for zinc, to the present data. This is perhaps surprising as most of the river water of the Niger Delta passes through areas of Pb-Zn-mineralization (Benue Valley, Abakaliki Province of Eastern Nigeria). Waskowiak (1962, p. 33) reported a value of 360 ppm of lead for globigerinids. He (Waskowiak, 1962, p. 83) found a very high proportion of the invertebrate shells studied by him to contain some lead. He considered some of the high values recorded from Red Sea invertebrates could be related to nearby lead-

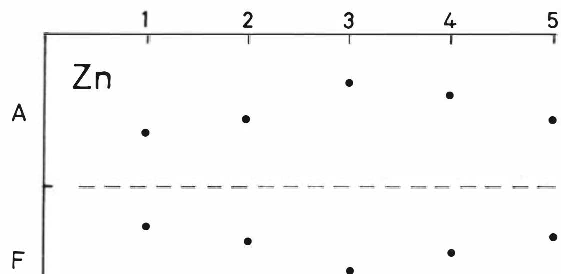

Fig. 21. Variation of content of Zn in sediment with depth for each of the complete transects. The figures 1 through 5 denote the stations.

zinc deposits. Price (1967, p. 522) found a lead concentration of 158 ppm in surface sediments from the Oslo Fjord. Chow and Patterson (1962, p. 265) reported 25–30 ppm for surface pelagic sediments and stated that there is much variation in surface lead values. Wedepohl (1965, p. 143) put forward the conclusion that the lead content of sediments is mainly taken up by clay minerals.

Zinc. Some discussion of this element has already been made in connexion with the section on lead. The mode of occurrence for Zn is irregular; only transect H suggests an increase in the zinc content with depth. Station I 4 shows the highest value. The correlation coefficient between depth of station and content of zinc is 0.46 (significant on 2% level), which indicates a significant tendency for enrichment in this metal with depth. Although the highest values for both lead and zinc occur in the sample from station I 4, which incidentally is not near to the principal drainage debouchment from the Pb–Zn deposits, lead and zinc are not significantly correlated in their occurrences. This would seem to argue against the possibility of these ore deposits influencing the trace-element content of the delta sediments. Sample I 4 was found to be rich in calcareous shell material, planktonic foraminifers, worms, molluscs and echinoids. Waskowiak (1962, p. 30) noted zinc contents of up to 180 ppm in the shell of globigerinids and 65 ppm for certain echinoids. Parker (1962, p. 75) reviewed the biologic importance of zinc in the ocean and remarked upon the great ability of some organisms for enrichment of this element. The zinc content of seawater is far less than were to be expected from the amount delivered to the ocean from the land. Parker's study of a Texas bay yielded values for zinc in the upper 15 cm of sediment of 10–18 ppm, which is much lower than those for the Niger Delta. Higher values were obtained for some plants and animals (highest 130 ppm for mullet). The zinc content can possibly be explained in terms of the formation of ZnS in the sediment. This would also account for the relatively high values for cadmium and the not unusual values for lead, as lead is not included in the sphalerite lattice whereas cadmium is. Owing to the low solubility product of zinc sulfide, this compound will tend to form ahead of others. The microbial origin of zinc sulfide ore deposits has been discussed by King (1967, p. 144); however, published information is scarce.

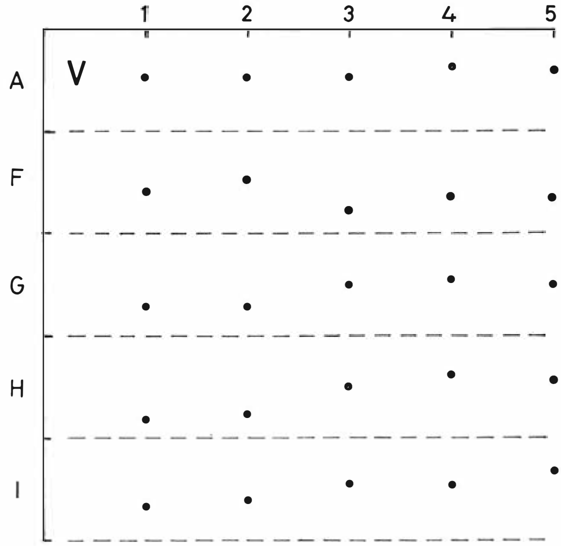

Fig. 22. Variation of content of V in sediment with depth for each of the complete transects. The figures 1 through 5 denote the stations.

Values obtained by Angino (1965) are much lower than those found in this study (total zinc in top 5 cm = 2 $\mu g/g$). Price (1967, p. 522) reported 265 ppm for zinc in sediments from the Oslo Fjord.

Vanadium. Transect I shows a gradual increase in values with depth for V (Fig. 22), whereas transects A, G and H display an increase in vanadium content up to and including station 4, but thereafter there is a drop. Transect F shows no clear tendency. The correlation coefficient between depth and vanadium content is 0.56, which is significant on the 1%-level, thus indicating a definite tendency for the amount of vanadium in the surface sediment to increase with depth. The values obtained in this study are of the same order of magnitude as those found for Antarctic glacial marine sediments by Angino (1966, p. 945) and Angino and Andrews (1968, p. 639). As indicated in that paper by Angino, vanadium is in our material enriched in some samples in relation to its abundance in the crust. It is interesting to note that the values for cores from Puerto Rico obtained by Angino (1965) are apparently less than (mean = 70 $\mu g/g$) the Niger Delta values. Holothurians and ascidians have often been reported to have a considerable ability for enriching vanadium—for example, the ash of one ascidian yielded

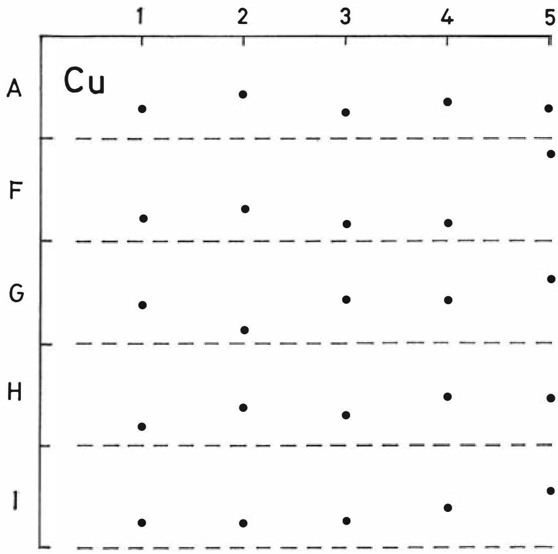

Fig. 23. Variation of content of Cu in sediment with depth for each of the complete transects. The figures 1 through 5 denote the stations.

1% of this element (Waskowiak, 1967, p. 34). Hirst (1962 *b*, p. 1159) found 49 ppm V in deltaic sands of the Gulf of Paria.

Copper. Transects I, H and G show a general tendency for copper to increase with depth. The samples from transect F fluctuate but show a final increase with depth (Fig. 23). Transect A displays no apparent trend. The average copper content for the samples is less than the crustal average (Taylor, 1964), although three of the samples from the 60 m depth exceed the crustal average for this element. The overall correlation of content of copper with depth is 0.60, which is significant on the 1%-level. There is thus a reasonable indication of enrichment of copper with depth. An organic source of copper is provided by certain gastropods and Mullin and Riley (1956, p. 119) reported 26–87 $\mu g/g$ for some of the soft parts of *Buccinum.*

Other organic sources of copper are globigerinids, other molluscs particularly oysters as well as crustaceans, the blood of which has the highest contents; haemocyanine contains 0.34–0.38% Cu (Waskowiak, 1962). The figures for the Niger Delta are on the whole higher than those found by Angino (1965, Table 20) for another tropical area (Puerto Rico) but are less than the results obtained by that author for Antarctic sediments (Angino, 1966, p. 945; Angino & Andrews, 1968, p. 639).

Nickel. The overall trend for nickel is to increase with depth, this being best shown by transects A, G and H. Transect I shows an increase up to the fourth station, while transect F does not show any particular characteristics. The correlation coefficient between depth and nickel content is 0.67 which is significant on the 1% level and may be taken to indicate a pronounced tendency for this element to increase in concentration away from the shore. All samples lie below the crustal average for Ni. Nickel is found in the shells of echinoids, mollusks and foraminifers. It is a much rarer constituent of the soft parts of molluscs than, for example, Mn, Cu, and Zn (Waskowiak, 1962). The values are somewhat higher on the average than the Puerto Rican and Antarctic data referred to in the foregoing.

Cobalt. Transects A, G, H and I show a tendency for the content of cobalt to increase with depth but transect F deviates from this pattern. The values for Co and depth of sample have a correlation coefficient of 0.51, which is significant on the 2%-level. Cobalt, as also nickel, are among the less common trace elements of the soft parts of molluscs. Waskowiak (1962, p. 39) reports that Ni is usually more common in the gut of molluscs than is Co; in the sediments here examined the

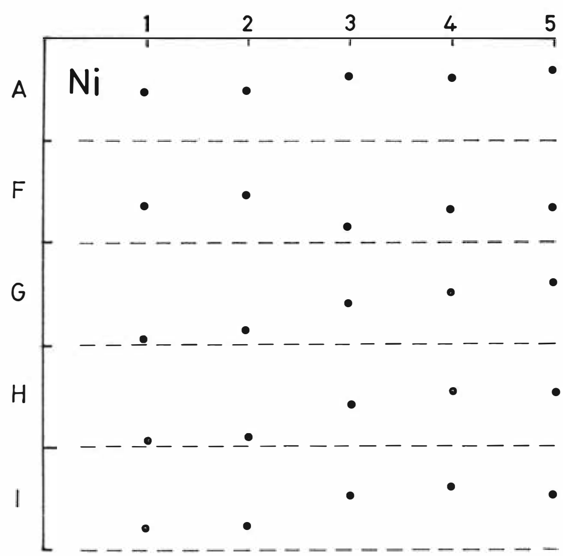

Fig. 24. Variation of content of Ni in sediment with depth for each of the complete transects. The figures 1 through 5 denote the stations.

concentration of nickel is on the average twice that of cobalt, but both are deficient in relation to the average crustal abundance of these elements. The cobalt content of only 0.4 ppm for the sediment of a Texan Bay, found by Parker *et al.* (1963, p. 30), is much lower than the lowest value obtained in the present study (2 mm). Parker (1966) has been able to show that Co may be involved in a two-phase cycle, one of which involves marine plants and the other the top layers of sediment.

Manganese. The graph of manganese concentration as a function of depth (Fig. 26) does not yield a clear picture of any definite relationship. Only one sample exceeds the crustal average for Mn and the mean value for this element in the samples analyzed suggests a deficiency in relation to the crust. The suggestion given by Fig. 26 is supported by the correlation coefficient between depth of sample and concentration of manganese, which is 0.05. It was thought that the occurrence of Mn might be connected to the Eh of the sediment; the correlation coefficient of -0.06 does not support this hypothesis. The distribution pattern for Mn differs considerably from that found for the other trace metals treated here. The manganese content reported for the sediments of a Texan bay by Parker *et al.* (1963, p. 30) lies well below the value found for the Niger Delta. Angino (1965) obtained contents somewhat lower than ours for Puerto Rico; the same worker (Angino, 1966, p. 945) found much higher values, in excess even of crustal abundance, for Antarctic marine sediments.

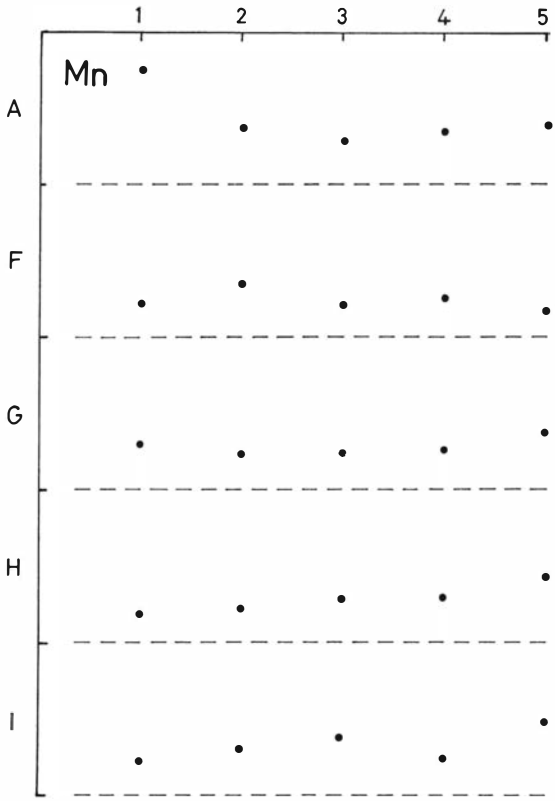

Fig. 26. Variation of content of Mn in sediment with depth for each of the complete transects. The figures 1 through 5 denote the stations.

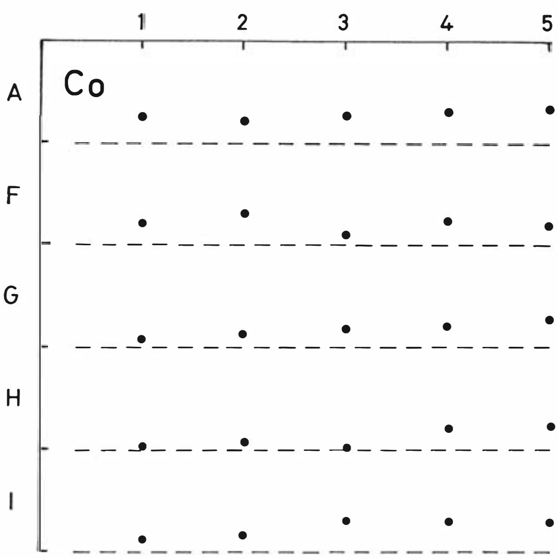

Fig. 25. Variation of content of Co in sediment with depth for each of the complete transects. The figures 1 through 5 denote the stations.

There does not appear to be any obvious nodule formation in the area at the present day, although some of the shells show coatings which might contain manganese (cf. Price, 1967, p. 512). Waskowiak (1962, p. 36) noted the importance of foraminifers in manganese concentration. Few of the organisms referred to by that author in his discussion of manganese reach up to the amounts found in the sediments here under discussion. Hirst (1962 *a*, p. 325) recorded a manganese content of 0.04% in delta sands of the Gulf of Paria.

Phosphorus. The graph of analyses against depth (Fig. 27) shows quite clearly that the content of phosphorus in the sediments displays a pronounced tendency to increase with depth. This is strongly supported by the correlation coefficient

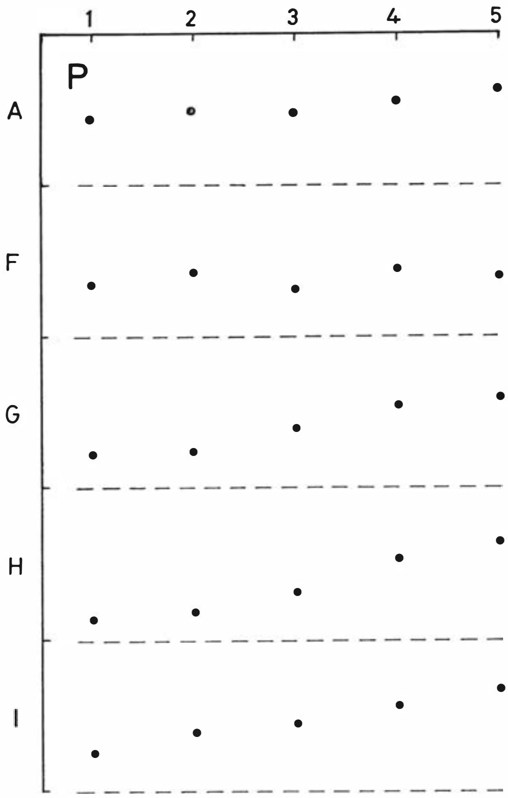

Fig. 27. Variation of content of P in sediment with depth for each of the complete transects. The figures 1 through 5 denote the stations.

of 0.78 (significant on < 1 % level). The correlation of the analysis values with the Eh determinations of this study was calculated and found not to differ significantly from zero. The phosphorus content of the sediments analysed is on the average less than the crustal average and in some of the samples very much less (minimum 200 $\mu g/g$). Three samples are slightly below the crustal average (930, 940, 980 $\mu g/g$); these are rich in fecal pellets. The samples from stations H 5 and I 5 do not contain much shell material ($CaCO_3 = 1.35\%$ respectively 3.60 %) while A 5 contains somewhat more shell ($CaCO_3 = 5.6\%$) as well as fecal pellets. This may indicate that the fecal pellets are one of the main sources of phosphate in the sediment. Brookes *et al* (1968, p. 408) believe the phosphate of sediments to be largely of organic origin.

Sulfur. The total sulfur content is represented in the values of Table XI. These values do not show any definite trend with depth (Fig. 28). The highest values for transects G, H and I occur at the middle station. The highest value for transect A occurs for the first station and for the second station for transect F. Checking the content of oxidizable organic matter against maximum content of sulfur shows that the samples with the highest organic contents for transects A, G, H and I also contain the highest amounts of sulfur. The correlation coefficient between the content of oxidizable organic substance and sulfur is 0.76, which is significant on the 0.1 %-level. There is therefore a clear relationship between these two variables and there can be little doubt that the main part of the sulfur in the sediment comes from the decomposing organic matter. The lowest sulfur value for our material is 90 $\mu g/g$ which was obtained in two sand samples. The highest value of 5700 $\mu g/g$ was determined in sample A 1 which was found to be rich in plant material. Interestingly, the correlation between E_h and sulfur content does not differ significantly from zero.

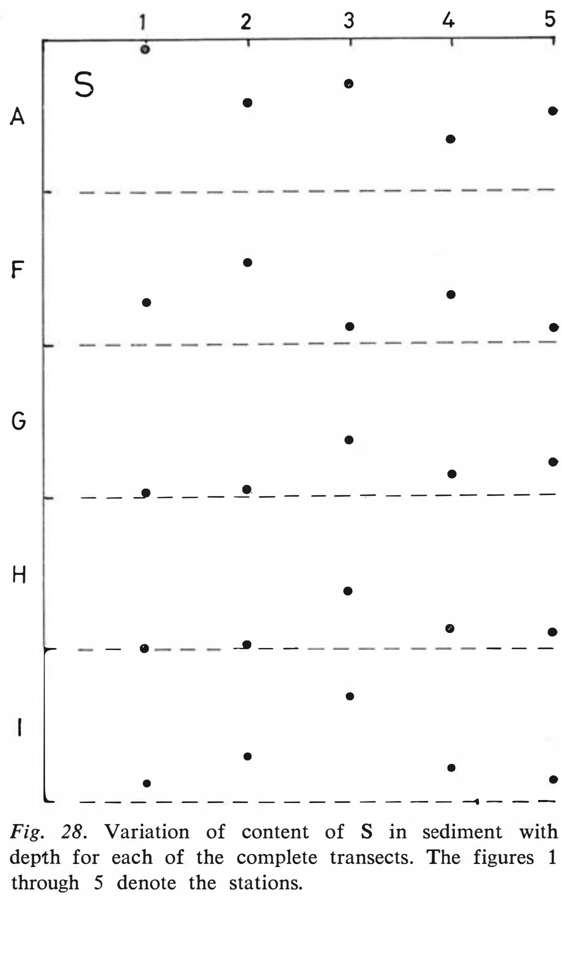

Fig. 28. Variation of content of S in sediment with depth for each of the complete transects. The figures 1 through 5 denote the stations.

This could possibly indicate that the sulfur is mostly present as sulfate and that reduction of sulfate ions in interstitial water by sulfate-reducing bacteria has not taken place (cf. Berner, 1964 *a*, p. 133). The relationship between sulfur content and E_h in the surface sediment is clearly a complicated question. The average sulfur content in the sediments analysed is about twice the crustal average (although the coefficient of variation is huge ($V \approx 95$). Pyrite is not uncommon as a primary ingredient of the shells of some agglutinating foraminifera in the delta sediments—an example for *Textilina mexicana* (Cushman) is shown in an electron micrograph (Fig. 29). Waskowiak (1962, p. 36) noted that some mollusc shells contain considerable amounts of S, partly as a constituent of the conchiolin.

Remarks

It is clearly not advisable to venture into an ambitious attempt at interpreting the relationships on the basis of the relatively few analyses available. However, the most strongly delineated trends exposed by the trace-element analyses will be considered.

The Niger Delta is on one side flanked by the active volcano Mt Cameroon and the extinct volcano Fernando Póo. The stations of transect A lie between these two and it might reasonably be expected that the trace element contents of the sediments could be influenced by the volcanic rock. (The beach sand along the coastal side of Mt Cameroon is dominated by basaltic material (Fig. 30).) Taylor (1964, Table 3) has given averages of trace elements in basalt. This table indicates that in relation to the continental crust the average basalt is considerably enriched in V, Mn, Co, Ni, Cu, Zn, whereas it is deficient in Pb and does not differ in Cd. Examination of the analyses of transect A shows that the sediments are enriched in Pb, Zn in relation to both basalt and the continental crust but are deficient in V, Cu, Ni, Mn. This would not seem to indicate that the basalts of Mt Cameroon and Fernando Póo are supplying sufficient material to the Bight of Biafra to counterbalance the sediments being delivered from the Niger complex and the rivers to the immediate east of Cameroon. It has already been suggested that the enrichment of Pb and Zn in the delta probably is not directly correlatable with the lead–zinc ore deposits of the hinterland. The above discussion could, however, serve as contrary evidence. In this connexion it is interesting to note that Turekian (1968, p. 609) considers that the concentration patterns of Co, Ni, Fe and Mn in deep-sea sediments, and their accumulation rates, may be reasonably explained by continental supply alone. A second clear indication arising from these data is that some of the trace elements show a tendency to increase in concentration with distance from the shoreline. Cd, Pb, Zn, V, Cu, Co show roughly the same order of magnitude of correlation. The correlation of P with depth is of a higher order of magnitude. Brookes *et al* (1968, p. 409) noted Cu, Co, Zn and Cd to be

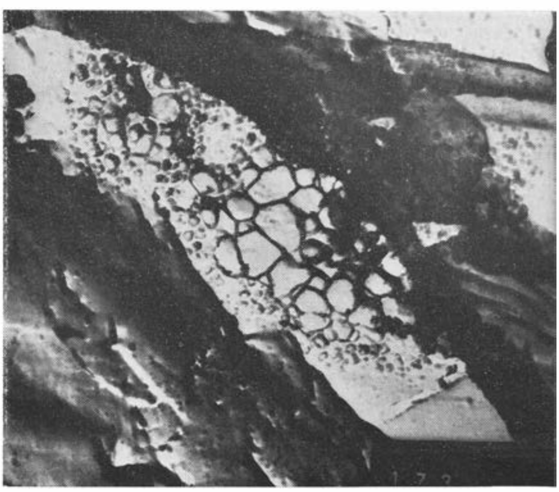

Fig. 29. Pyrite in shell of *Textilina mexicana* (Cushman) (× 1250). Electron micrograph by R. Hallberg.

Fig. 30. Tracks in dark grey, volcanic, intertidal beach sand, Bota, Cameroun.

enriched in surface samples of their material from the continental shelf off the coast of Southern California and found the latter two elements to be highly correlated ($r = +0.73$), which led them to the suggestion that the processes controlling the distribution of these metals might be the same. The correlation coefficient between Zn and Cd in our material is a low 0.35. This, on the basis of 25 analyses, may be fortuitous but if not, might indicate that only part of the zinc and cadmium are combined in sulfide (taking it that some Cd becomes incorporated in the lattice of ZnS). This requires an explanation of the origin of the main part of the zinc sulfide in the sediment. A possible source could be detrital. Hirst (1962 *b*, p. 1163) found for deltaic sands of the Gulf of Paria 5.3 ppm Co and 17 ppm Ni, both of which lie below the figures obtained for the Niger Delta sands. His values for "delta clay" are also much lower than comparable Nigerian sediments. Lower values for Cu and Pb were also obtained (Hirst, 1962 *b*).

Statistical analysis of the geochemical data

Principal coordinate analysis: The association matrix used in this paper is that of Gower (MS) who has proposed a useful measure, which leads to a positive definite similarity matrix. For quantitative characters of character k with values $x_1, x_2, \ldots x_n$ Gower's coefficient for the total sample of n individuals is defined as

$$s_{ijk} = 1 - |x_i - x_j|/R_k.$$

Here R_k is the range of character k. The matrix S_{ij} with elements s_{ijk} ranges in value between 0 and 1.

In a numerical taxonomic study there will be measurements on p variates for each of n individuals. The interrelationships between these variates will be estimated by means of some form of coefficient of association, a_{ij}, between all pairs of individuals. These form the "association matrix" A.

We consider the symmetric matrix A of order n. The eigenvalues of A are $\lambda_1, \ldots \lambda_n$ and its eigenvectors are: $b_1, b_2, \ldots b_n$. These form the matrix B of order n. In applying this in numerical taxonomy, one takes the elements of the i-th row as the coordinates of a point, T_i, in n-space. The distance, d_{ij}, between P_i and P_j is then given by

$$d_{ij}^2 = \sum_{r=1}^{n} b_{ir}^2 + \sum_{r=1}^{n} b_{jr}^2 - 2\sum_{r=1}^{n} b_{ir} b_{jr}. \tag{2}$$

Thus, for rows 2 and 3

$$d_{23}^2 = \sum_{r=1}^{n} b_{2r}^2 + \sum_{r=1}^{n} b_{3r}^2 - 2\sum_{r=1}^{n} b_{2r} b_{3r}. \tag{3}$$

If the eigenvectors of A are normalized so that the sums of squares of their elements are equal to the corresponding eigenvalues,

$$b_{ir}^2 = \lambda_r,$$

then

$$A = b_1 b_1' + b_2 b_2' + \cdots + b_n b_n'. \tag{4}$$

and

$$d_{ij}^2 = a_{ii} + a_{jj} - 2a_{ij}. \tag{5}$$

By this means, one may represent a multivariate sample of size n as points $T_l, \ldots T_n$ in a Euclidean space. The relationship between the eigenvalues and eigenvectors of the association matrix A are indicated below:

		Eigenvalue		
		λ_1	$\lambda_2 \cdots \lambda_n$	
		Eigenvectors		
	T_1	b_{11}	$b_{12} \cdots b_{1n}$	
Point	T_2	b_{21}	$b_{22} \cdots b_{2n}$	
	.	.	.	.
	.	.	.	.
	T_n	b_{n1}	$b_{n2} \cdots b_{nn}$	
Centroid	$\bar{T}$	$\bar{b}_1$	$\bar{b}_2 \cdots \bar{b}_n$	

Gower (1966) has demonstrated that it is legitimate to use the methods of principal components as a Q technique on the coordinates of the T_i to find the best fit in fewer dimensions. In accord with what is usually observed in principal components, it may be expected that a good representation of the set of points may be obtained in a reduced number of dimensions when some of the eigenvalues are small. That is if, say λ_r is small, the contribution of $(b_{ir}-b_{jr})^2$ to the distance between T_i and T_j will be small. If λ_r is large, but the b_{ir} corresponding to it are not greatly different, then $(b_{ir}-b_{jr})^2$ will be small. Hence, the only coordinates supplying much to the distances are those which display a wide range of variation in the elements of the eigenvectors and which are associated with a large eigenvalue. In common with what is found in principal component analysis, the distances may often be adequately expressed by two or three vec-

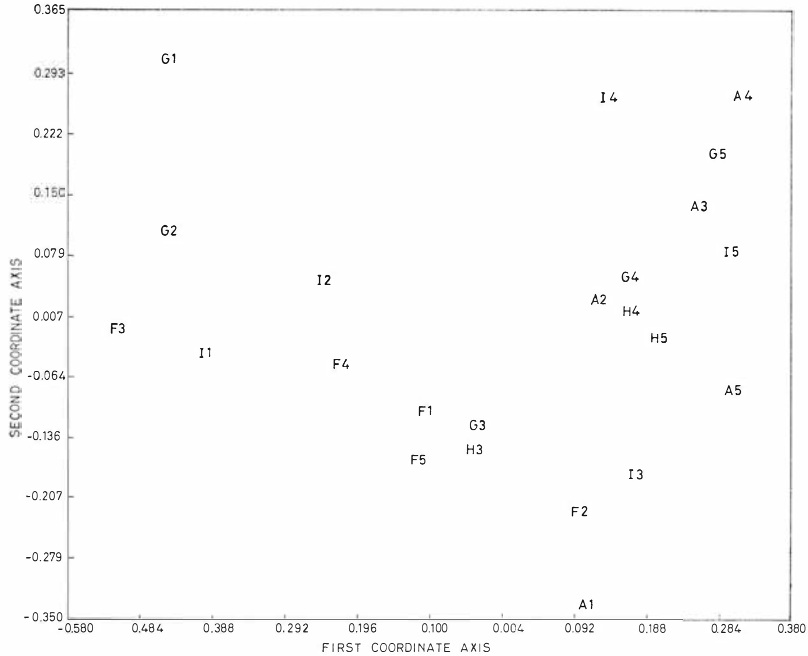

Fig. 31. Plot of the first two sets of principal coordinates for the sedimentary and geochemical data.

tors. A further analog with the R-technique of principal components is that the elements of the first eigenvector may often be found to have similar elements, relating to the mean value of all the elements of A. This mean value is not important to the problem at hand, as the distances are invariant for any constant added to A. The addition of such a constant will, however, result in different coordinate values T_i and different eigenvalues and these new points are an orthogonal transformation of the original set after a change of origin. Interest naturally attaches to determining which transformation gives the best fit with a reduced number of coordinates.

This mean values is unimportant in this connexion as the addition of any constant to the association matrix A leaves the distance between T_i and T_j invariant. Gower (1966, p. 330) adjusts for the means in the following way. It is always possible to adjust matrix A so that it has a zero eigenvalue without altering the distance between T_i and T_j, for if $\bar{a}_i$ is the mean value of the i-th row or column of A, and $\bar{a}$ is the overall mean, a matrix α_{ij} may be defined in terms of the elements

$$\alpha_{ii} = a_{ij} - \bar{a}_i - \bar{a}_j + \bar{a}. \qquad (6)$$

Inasmuch as every row and column of matrix a_{ij} sums to zero, α_{ij} has a zero eigenvalue.

The computer program used for the calculations first forms the association matrix A, which is then transformed to matrix α_{ij} by equation (6). The eigenvalues and eigenvectors of matrix α_{ij} are computed and the eigenvector is scaled so that its sum of squares is equal to the corresponding eigenvalue. The i-th row of the matrix of eigenvectors represents the coordinates of a set of points T_i whose distances apart are given by the best approximations to $(a_{ii} + a_{jj} - 2a_{ij})^{\frac{1}{2}}$ in the chosen number of dimensions.

In summary, the method of principal coordinate analysis finds the coordinates of each individual of a sample, referred to principal axes, which preserve the distances, suitably defined, between the individuals. It is used here to identify such relationships, expressed as a tendency to form clusters, as exist in the material. The analysis accounted for here is grounded on 18 samples on each of which the following variables have been determined: interstitial pH, interstitial E_h, interstitial O_2, $CaCO_3$-content, content of oxidizable organic matter, median of the sediment, Cd, Pb, Zn, Co, Ni, V, Mn, Cu, P, S.

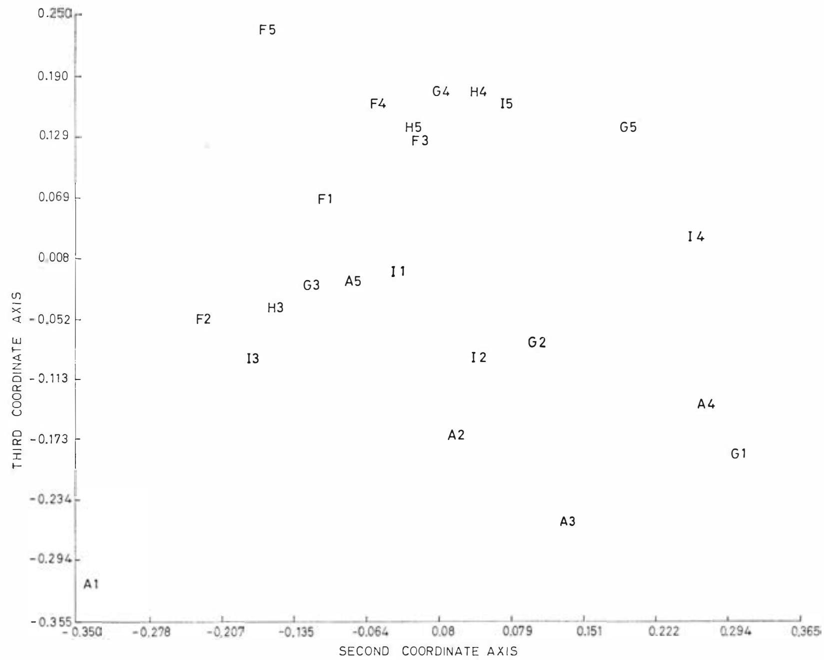

Fig. 32. Plot of the second and third sets of principal coordinates for the sedimentary and geochemical data.

The slow decrease in the eigenvalues of the association matrix indicates that there is much near-random variation in the observations. Thus the first ten eigenvalues are: 1.5642, 0.5945, 0.5151, 0.4295, 0.3835, 0.2938, 0.2517, 0.2111, 0.2033, 0.1845. This suggests that pronounced clustering is not likely to exist in the data.

The plot of the first two sets of principal coordinates is shown in Fig. 31. The stations of transect F show up a group in the lower left-hand sector of the diagram and those of transect A group to the right. A2–G4–H4–H5 form one small group and F1–F5–G3–H5 another. It has been noted elsewhere in the text that transect F behaves anomalously in relation to the other transects, particularly as regards the distributions of the trace elements, and this is clearly brought to light by the present analysis. The plot of the second and third principal coordinates (Fig. 32) shows the same tendency for the stations of transect A to form a dispersed though isolated group in the bottom of the figure and those of transect F to group more closely. The percentage residual for two coordinates is 35.8% and for three coordinates, 26.3%.

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Appendix

ANALYSIS OF SEDIMENTS FOR TRACE ELEMENTS DETERMINATION OF Zn, Cu, Pb, Mn, Ni, Cd, Co AND V

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Two g of the finely ground sample were weighed into a small platinum dish, heated for 6 hours at 500°C in a muffle furnace, decomposed by repeated heating with HF and $HClO_4$ to near dryness in a radiator. The residue was dissolved by warming with dilute HCl; the solution was filtered, diluted to 50 ml, and stored in a polythylene bottle.

Vanadium was determined spectrophotometrically after extraction with N-benzoylhydroxylamine, using a modification of the method given by Ryan (1960).

The other metals were determined by means of a Techtron AA-4 atomic absorption spectrophotometer. The solutions were mostly aspirated directly into the air-acetylene flame, but in the analysis of Mn the sample solution was first diluted. The absorbance of Pb was measured at 2833 Å (instead of the most sensitive line 2170 Å), using a scale expansion of 5-times. The values obtained for Co and Ni were corrected for background absorption by measuring the absorbance at a nearby "non-absorbing" line.

Determination of P and S

The determination of P was performed on a separate sample according to Baadsgaard and Sandell (1954), after the destruction of organic material by heating in a platinum crucible at 500°C for 4 hours.

For the determination of total S another portion was melted with Na_2CO_3 and KNO_3 (20 : 1) in a platinum crucible, the thoroughly disintegrated melt was extracted with warm water, and the solution filtered. An aliquot of the filtrate was acidified with HCl, evaporated to dryness, and sulphate reduced to H_2S and determined as methylene blue according to Gustafsson (1960).

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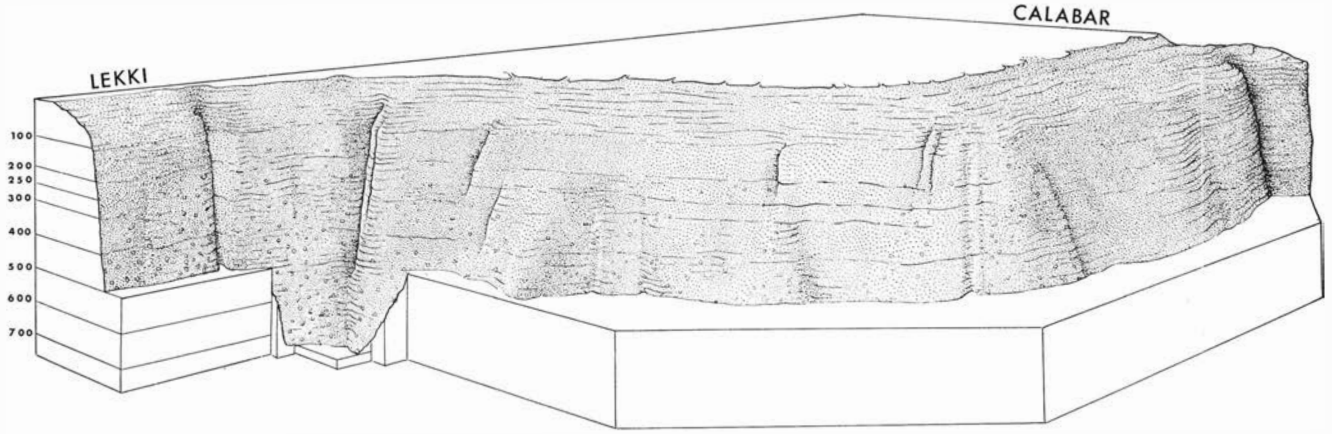

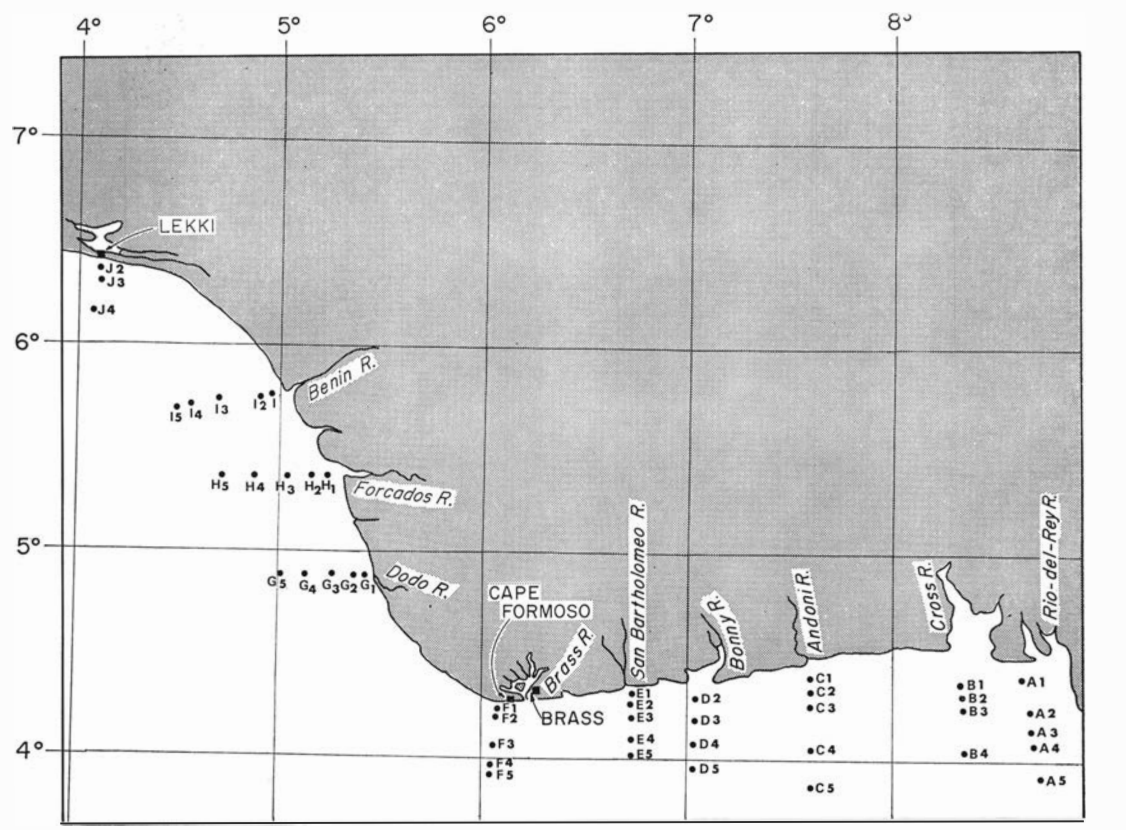

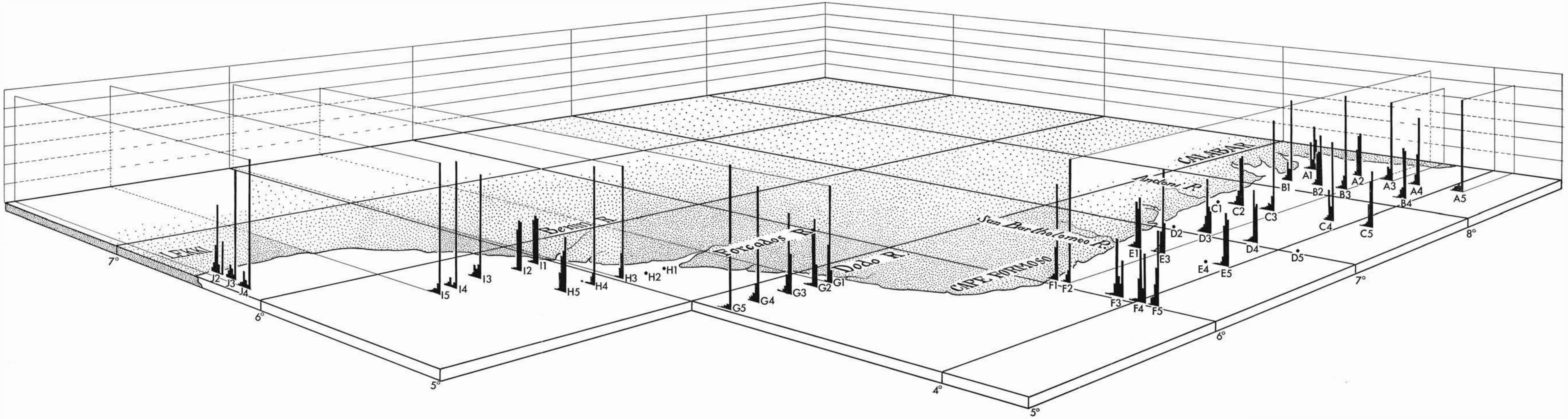

Fig. 1. Upper right. Location map for the stations occupied during the cruise in 1966. Upper left. Reconstruction of the Niger Delta, based on echosounding, the Admiralty charts and data published in Allen (1964). Bottom: Schematic histograms of the sediment obtained at the stations occupied; observe the preponderance of fine-grained sediment.